III Congresso Ibérico de Paleontologia

Lisboa, Portugal, 7 a 10 de Julho de 2010

XXVI Jornadas de la Sociedad Española de Paleontología

Excursões • Excursiones

Guia das excursões de campo do

III Congresso Ibérico de Paleontologia
XXVI Jornadas de la SEP

Departamento de Geologia
Faculdade de Ciências de Lisboa
Universidade de Lisboa

http://geologia.fc.ul.pt/

Capa e grafismo
Carlos Marques da Silva

Lisboa, 2010

III Congreso Ibérico de Paleontología

Lisboa, Portugal, 7 a 10 de Julio de 2010

XXVI Jornadas de la Sociedad Española de Paleontología

A Ibéria no centro das relações atlanto-mediterrânicas
Iberia en el centro de las relaciones atlántico-mediterráneas

Guia das excursões
•
Guía de las excursiones

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Carlos Marques da **Silva**, Vanda Faria dos **Santos**, Mário Cachão, Ana **Santos**, Eduardo **Mayoral**.

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Excursão pré-congresso: 7 de Julho de 2010 (8h00-16h00)
Excursión pre-congreso: 7 de Julio de 2010 (8h00-16h00)

Península de Setúbal

> Icnitos de dinossáurios jurássicos e cretácicos
> Bioerosão associada a paleolitoral rochoso miocénico
> Paragem na Azóia para feijoada de marisco local

> Icnitas de dinosaurios jurásicos y cretácicos
> Bioerosión en un paleolitoral rocoso mioceno
> Parada en Azóia para degustar la “feijoada” de marisco local

Legenda

① Pedreira do Avelino (Zambujal).

Icnitos de dinossáurios saurópodes jurássicos.
Icnitas de dinosaurios saurópodos jurásicos.
N 38º 27' 14.40'' W 09º 07' 23.97''

Bibliografia: V. Santos, 2008: 82-85.

② Pedra da Mua e Lagosteiros (Cabo Espichel).

Icnitos de dinossáurios ornitópodes e terópodes jurássicos e cretácicos.
Icnitas de dinosaurios saurópodos y terópodos jurásicos y cretácicos.
Mua: N 38º 25' 20.00'' W 09º 12' 58,55''; Lagosteiros N 38º 25' 32.76'' W 09º 12' 58.66''

Bibliografia: Dantas et al., 1994: 43-48; Lockley et al., 1994: 27-35; Meyer et al., 1994: 121-122; V. Santos, 2008: 86-90; V. Santos, 2008: 91-92 .

③ Almoço no / Comida en el "Retiro dos Amigos", Azóia.

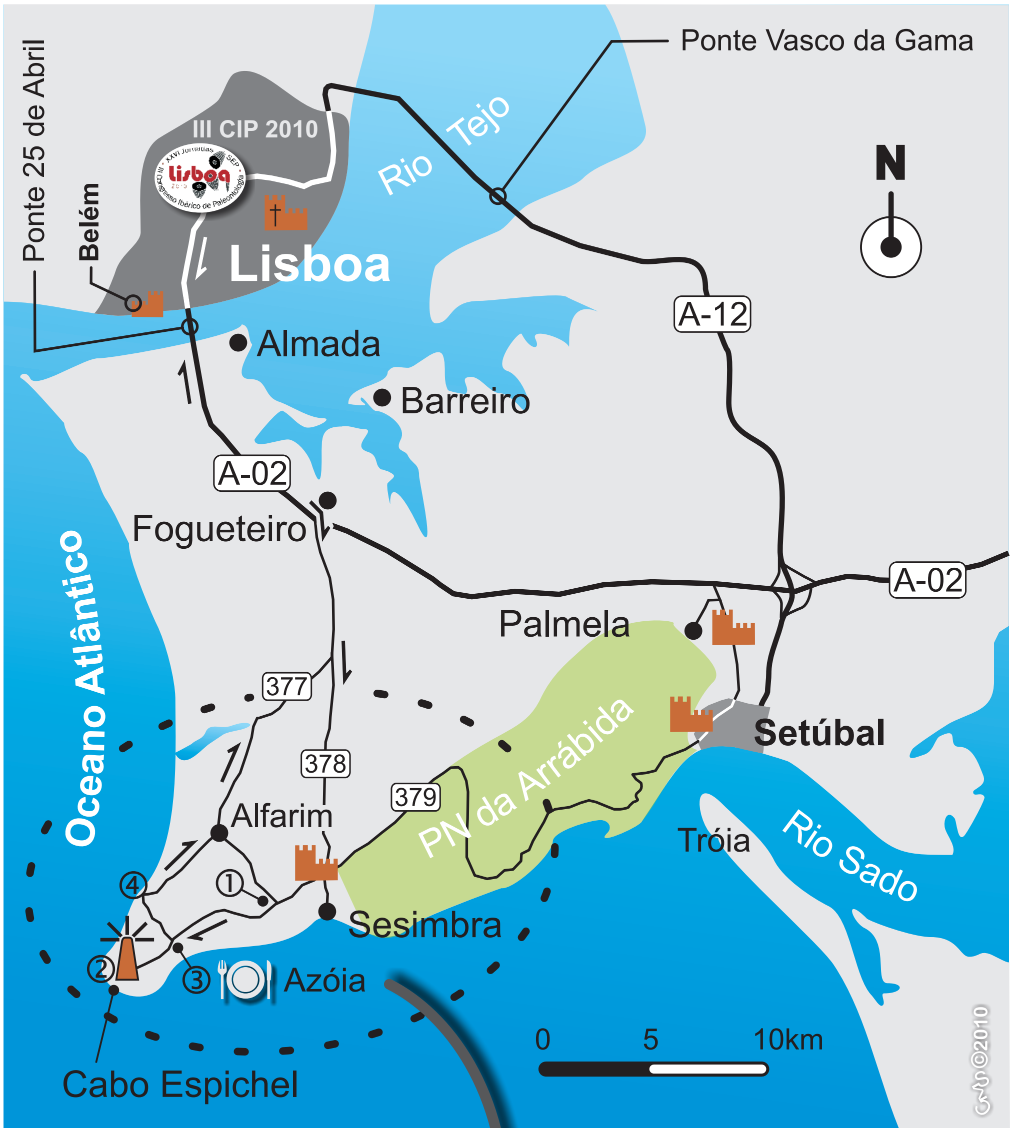
Feijoada de marisco num simpático restaurante local.
"Feijoada" de marisco en un simpático restaurante local.
N 38º 25' 45.18'' W 09º 11' 15.76''

Contacto: 21 083 14 82.

④ Praia da Foz da Fonte.

Bioerosão em paleolitoral rochoso miocénico.
Bioerosión en un paleolitoral rocoso mioceno.
N 38º 27' 07.42'' W 09º 12' 05.60''

Bibliografia: A. Santos et al., 2010: 35-43; Silva et al. 1995:157-158 .


Ponte Vasco da Gama
Ponte 25 de Abril
Belém
III CIP 2010
Lisboa
Rio Tejo
N
A-12
Almada
Barreiro
A-02
Fogueteiro
Oceano Atlântico
A-02
Palmela
377
378
379
PN da Arrábida
Setúbal
Alfarim
Tróia
Rio Sado
Sesimbra
Azóia
Cabo Espichel
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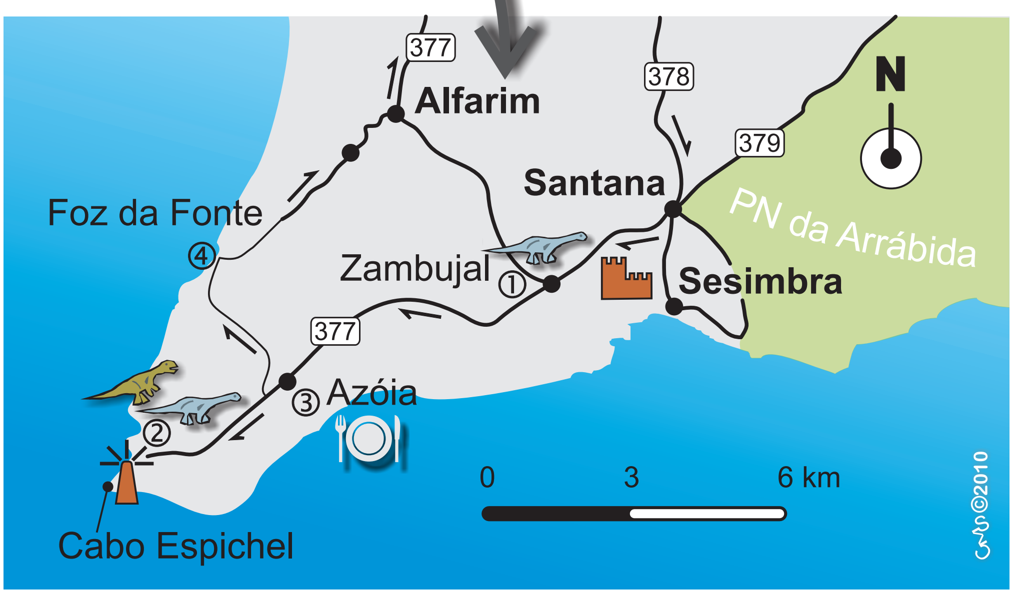
377
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Santana
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PN da Arrábida
Zambujal
Sesimbra
377
Azóia
0 3 6 km
Cabo Espichel

Excursão pós-congresso: 10 de Julho de 2010 (8h00-20h00)
Excursión post-congreso: 10 de Julio de 2010 (8h00-20h00)

Pedreira do Galinha - Alcanede - Óbidos

> Icnitos de dinossáurios saurópodes e terópodes jurássicos
> Icnitos de dinossáurios terópodes jurássicos
> Visita à vila histórica de Óbidos e prova de ginjinha

> Icnitas de dinosaurios saurópodos y terópodos jurásicos
> Icnitas de dinosaurios terópodos jurásicos
> Visita a la villa histórica de Óbidos y degustación de ginjinha

XXVI Jornadas SEP · III Congresso Ibérico de Paleontologia · lisboa 2010

Legenda

① Pedreira do Galinha (Bairro).

Icnitos de dinossáurios saurópodes jurássicos.
Icnitas de dinosaurios saurópodos jurásicos.
N 39º 34' 11.99'' W 08º 35' 21.64''

Bibliografia: V. Santos, 2008: 50-54; V. Santos et al., 2008: 79-80; V. Santos et al., 2010: 409-422.

② Almoço no / Comida en el "O Transmontano", Bairro.

Refeição num simpático restaurante local.
Comida en un simpático restaurante local.
N 39º 34' 19.55'' W 08º 35' 56.72''

Contacto: 249 521513.

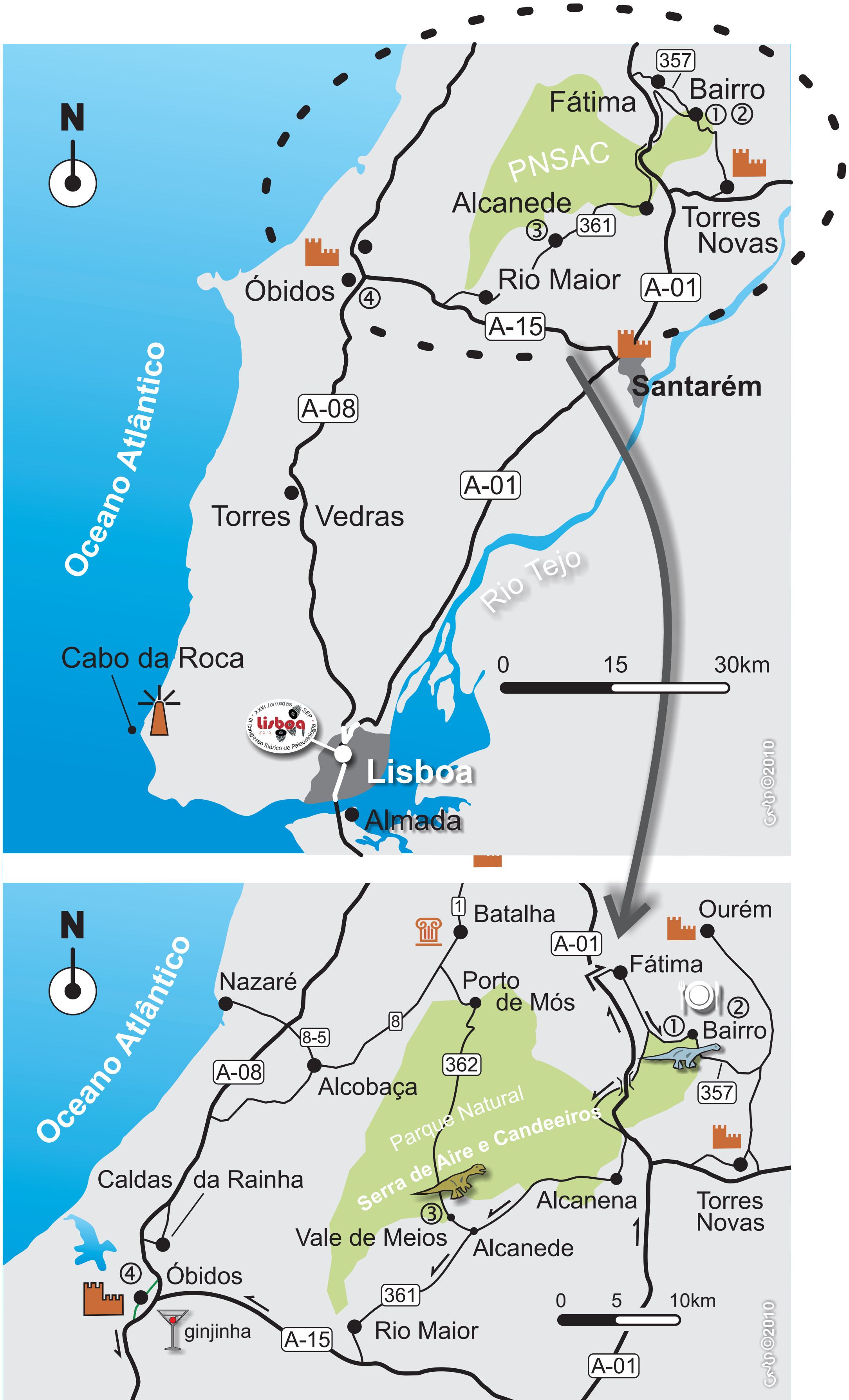
③ Vale de Meios (Alcanede).

Icnitos de dinossáurios terópodes jurássicos.
Icnitas de dinosaurios terópodos jurásicos.
N 398 27' 28.18'' W 08º 49' 15.40''

Bibliografia: V. Santos, 2008: 55-58; V. Santos et al., 2008: 80.

④ Óbidos.

Visita à vila histórica de Óbidos e degustação da afamada ginjinha local.
Visita a la villa histórica de Óbidos y degustación de la famosa ginjinha local.
N 39º 21' 43.13'' W 09º 09' 27.41''


N
Oceano Atlântico
Fátima
Bairro
357
PNSAC
Alcanede
361
Torres Novas
Óbidos
Rio Maior
A-01
A-15
Santarém
A-08
Torres Vedras
A-01
Rio Tejo
Cabo da Roca
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15
30km
Lisboa
Almada
N
Oceano Atlântico
Batalha
1
A-01
Ourém
Nazaré
Porto de Mós
Fátima
8
8-5
Bairro
A-08
362
Alcobaça
357
Parque Natural
Serra de Aire e Candeeiros
Caldas da Rainha
Alcanena
Torres Novas
Vale de Meios
Alcanede
Óbidos
361
0
5
10km
ginjinha
A-15
Rio Maior
A-01

Bibliografia

Dantas, P., Lockley, M.G., Meyer, C., & Santos, V.F. 1994. Foot-print evidence for limping dinosaurs from the Upper Jurassic of Portugal. Gaia, 10: 43-48.

Lockley, M.G.; Meyer , C.A. & Santos, V.F. 1994. Trackway evidence for a herd of juvenile sauropods from the Late Jurassic of Portugal. Gaia, 10: 27-35.

Lockley, M.G., Pittman, J.G., Meyer, C.A., & Santos, V. F. 1994. On the Common Occurrence of Manus-dominated Sauropod Trackways in Mesozoic Carbonates. Gaia, 10: 119-124.

Meyer, C.A., Lockley, M.G., Robinson, J.W. & Santos, V.F. 1994. A comparison of well- preserved sauropod tracks from the Late Jurassic of Portugal and the United States: Implications. Gaia: 10: 57-64.

Santos, A.G., Mayoral, E., Silva, C.M. da, Cachão, M. & Kullberg, J.C. 2010. *Trypanites* Ichnofacies: Palaeoenvironmental and tectonic implications. A case study from the Miocene disconformity at Foz da Fonte (Lower Tagus Basin, Portugal). Palaeogeography, Palaeoclimatology, Palaeoecology, 292: 35-43.

Santos, V.F. 2008. Pegadas de Dinossáurios de Portugal. Museu Nacional de História Natural da Universidade de Lisboa, Lisboa, 124 pp.

Santos, V.F., Silva, C.M. & Rodrigues, L.A. 2008. Dinosaur Track sites from Portugal: scientific and cultural significance. Oryctos, 8: 77-88.

Santos, V.F., Moratalla, J.J. & Royo-Torres, R. 2009. New sauropod trackways from the Middle Jurassic of Portugal. Acta Palaeontologiaca Polonica, 54(3): 409-422.

Silva, C.M. da, Cachão, M., Martinell, J. & Domènech, R. 1999. Bioerosional evidence of rocky palaeoshores in the Neogene of Portugal. Bulletin of the Geological Society of Denmark, Copenhagen, 45: 156-160.

GAIA Nº 10, DEZEMBRO/DECEMBER 1994, pp. 43-48 (ISSN: 08715424)

FOOTPRINT EVIDENCE FOR LIMPING DINOSAURS FROM THE UPPER JURASSIC OF PORTUGAL[1]

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ABSTRACT: Two examples of Late Jurassic trackways from Cabo Espichel, Portugal - one of a large theropod, the other of a sauropod - reveal alternating long and short steps indicative of irregular or "limping" gaits. The reasons for this limping behavior are not known, but recent studies suggest that such irregular trackways may be more common than previously supposed. We also review some simple quantitative guidelines for standardizing measurements used in the description of irregular trackways attributed to limping animals.

RESUMO: Nas jazidas do Jurássico superior do Cabo Espichel, Portugal, existem duas pistas (uma produzida por um grande terópode e outra deixada por um saurópode) que evidenciam passos longos e curtos, alternados, indicando uma locomoção irregular de dinossáurios que "coxeavam". As razões deste comportamento não são conhecidas, mas estudos recentes sugerem que estas pistas com passo irregular não são tão raras como se supunha. Procedemos à padronização de medidas usadas na descrição de pistas irregulares atribuídas a animais que coxeavam.

INTRODUCTION

The literature on fossil vertebrate trackways contains few well-documented examples of irregular trackways. Most trackways provide evidence of animals that walked in a straight line with steps (or paces) that are very regular. Some trackways curve a little, or occasionally provide evidence of sharp turns (LOCKLEY, 1991). Others show slight increases or decreases in step length through several consecutive steps and so indicate animals that were speeding up or slowing down, either deliberately, or in response to changing substrate conditions. We report here on another type of trackway configuration which reveals alternating long and short steps. To date we know of only one well-documented example of this phenomenon - namely the trackway of a limping theropod from the Middle Jurassic of Morocco (ISHIGAKI, 1986; see LOCKLEY, 1991, and LOCKLEY *et al.*, 1994, *in press*, for summary in English). In the case of the trackway described by Ishigaki, we calculated an average short and long step length of about 63 cm and 79 cm from his published illustration, and so calculated a short: long step ratio of 0.80:1.00 (= 80%). In simple terms,

(1) Work supported by Junta Nacional de Investigação Científica e Tecnológica (JNICT), Câmara Municipal de Sesimbra (Sesimbra Municipal Region) and the University of Colorado at Denver Dinosaur Trackers Research Group.

the long step is consistently about 25% longer than the short step. We use this ratio to provide a measure of the degree of limping or irregularity. We define limping as an irregular gait in which one leg or foot is favored over the other, resulting in consistent differences in the length of alternate steps. FARLOW (*written commun.*, 1994) has suggested that such patterns may not be indicative of "limping" in a strict sense, but may instead indicate that and animal favored its right or left side. We agree that this is a possibility, and note that some human athletes, *e.g.*, soccer players, favor a particular foot, and so may be left or right-footed.

MATERIAL

THEROPOD TRACKWAY

During the course of an ongoing study of Upper Jurassic trackways at Cabo Espichel, southwest of Lisbon, Portugal we documented two trackways of limping dinosaurs. The first occurs on a limestone bedding plane at Praia do Cavalo, near Cabo Espichel, Portugal. The track-bearing bed has been assigned to the Lower Portlandian (Portlandian A, *sensu* RAMALHO, 1971). The trackway can be attributed to a large theropod with a foot length of about 67 cm and corresponding foot width of 56 cm (Fig. 1). The step lengths vary between 172 and 212 (average about 193 cm), with consecutive short and long pairs (in a single stride) varying by as much as 38 cm (maximum short: long step ratio of 0.82:1.00 = 82%; mean ratio = 87%). The strides (consecutive pairs of steps) however are much more consistent in length – as should be expected (TABLE I).

The theropod trackway consistently shows that the right to left step length (R-L) is shorter (mean 179.6 cm) than the left to right (L-R mean = 205.8 cm). In the ten consecutive steps we measured the R-L step length is 0.86, 0.89, 0.93, 0.85 and 0.83 of the L-R step length. From this we infer that the animal was suffering from some form of recent or old injury to its left foot or leg. We make this inference based on observations of limping behavior in modern bipeds (injured humans), and comparisons with the Moroccan example where the injured foot has been identified by the abnormal configuration of toe impressions (LOCKLEY *et al.*, 1994, *in press*). In both cases the short step precedes the placement of the injured foot and the long step follows.

In order to obtain complete information for the trackway we also measured nine consecutive strides (TABLE I). In theory a completely regular series of long and short steps will produce a series of strides of the same length - regardless of the difference in length between the steps. This principle can be demonstrated in the case of the Praia do Cavalo trackway. The difference between the mean step length

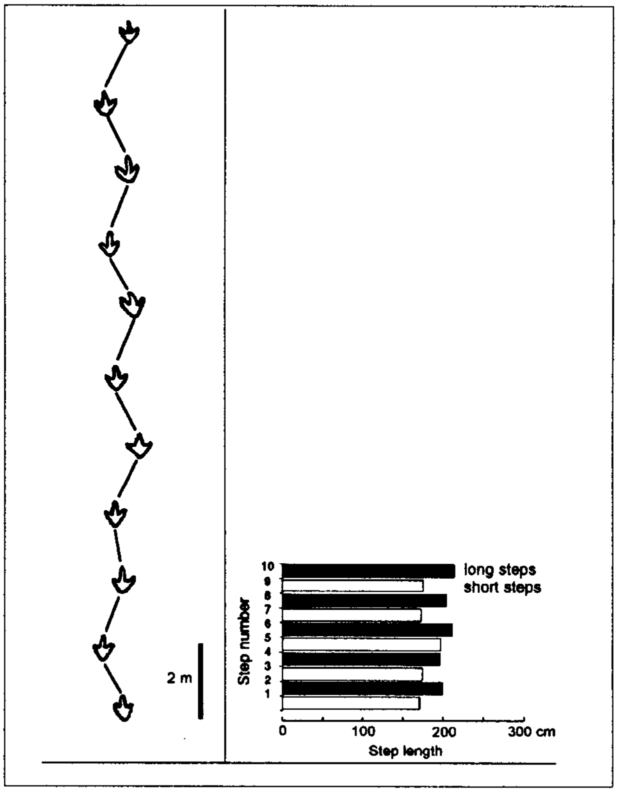

Fig. 1 - Map of trackway of limping theropod, Praia do Cavalo, Upper Jurassic (Portlandian A). Note length of alternating long and short steps.

and the maximum and minimum values is about 11% in each case (standard deviation = 15.47). By contrast the difference between the mean stride length and maximum and minimum values is only about 5% (standard deviation = 10.56). If we exclude the two extreme stride values, (in brackets in TABLE I), the maximum/mean and minimum/mean differences are reduced to only 1.7 and 3.7% (standard deviation = 6.34). From such observations we conclude that the former value (ratio between mean step and maximum and minimum values) provides another measure of the ratio between short and long steps, whereas the later value (pertaining to stride lengths) is an independent measure of changing step and stride lengths that is largely or completely unrelated to the ratio of consecutive step lengths in individual strides.

SAUROPOD TRACKWAY

We also encountered a second example of a dinosaur trackway with alternating long and short steps. This second example, discovered at Lagosteiros Bay, near Cabo Espichel, is attributable to a limping sauropod. The trackway occurs on one of eight track-bearing bedding planes exposed on the southside of the bay (see LOCKLEY, MEYER & SANTOS, 1994) and is assigned to track bed number 5 in the upper Portlandian (Portlandian B). As shown in TABLE II, the

TABLE I
Trackway data for limping theropod, Praia do Cavalo, Upper Jurassic (Portlandian A).

TRACK Nº	PES LENGTH*	PES WIDTH	STEP LENGTH	DIFFERENTIAL	STRIDE LENGTH
R1	68	58			
			172		
L1	68	58		28	
			200		
R2	(73)$^{+}$	(54)		24	R1-R2 [355]°
			176		
L2	(66)	(60)		21	L1-L2 370
			197		
R3	(65)	-		01	R2-R3 360
			198		
L3	68	57		14	L2-L3 380
			212		
R4	65	55		38	R3-R4 [393]
			174		
L4	64	54		31	L3-L4 378
			205		
R5	65	55		27	R4-R5 375
			178		
L5	-	55		37	L4-L5 378
			215		
R6	65	65			R5-R6 375
MEANS	**66.7**	**56.1**	**192.7**	**24.5**	**373.8**
			[R-L 205.8]		
			[L-R 179.6]		
STANDARD DEVIATION			**15.47**		**10.56**

* All measurements in centimeters. ($^{+}$) Approximate measurements. [°] Extreme values.

sauropod has an average pes length and width of about 68.5 and 49 cm respectively, with an average step length of 148 cm. Because sauropods were quadrupedal animals, ichnologists have the options of measuring step and stride lengths from pes to pes, from manus to manus, or both. Due to the exposed location of the trackway on a precipitous bedding plane 30-60 m above sea level we were obliged, for safety, to work on ropes. For this reason we were unable to obtain all step and stride measurements throughout the entire trackway (L1-R23). However we did obtain 16 consecutive step measurements, and eight consecutive stride lengths for the left side of the trackway (TABLE II).

Our data shows that the lengths of the short steps (L-R) and long steps (R-L) varies between 120 (mean 138) and 160 cm (mean 157). The overall average is about 148 cm, with consecutive short and long pairs (in a single stride) varying by as much as 40 cm (maximum differential ratio of 0.75:1.00 = 75%; mean ratio 0.87%). Based on the reasoning presented above, we consider that the trackway is indicative of a limping sauropod with an injury to its right foot, or right side.

TABLE II
Trackway data for limping sauropod, Lagosteiros Bay, Upper Jurassic (Portlandian B).

TRACK Nº	PES LENGTH*	PES WIDTH	STEP LENGTH	DIFFERENTIAL	STRIDE LENGTH
L2	72	48			
			144		
R3	-	-		11	
			155		
L3	70	50		12	L2-L3 220
			143		
R4	-	-		14	
			157		
L4	73	50		16	L3-L4 230
			141		
R5	66	45		21	
			162		
L5	-	-		18	L4-L5 238
			140		
R6	72	55		15	
			155		
L6	65	45		5	L5-L6 220
			150		
R7	-	-		10	
			160		
L7	-	-		23	L6-L7 212
			137		
R8	70	51		15	
			152		
L8	69	48		17	L7-L8 (185)
			135		
R9	-	-		12	
			147		
L9	73	49		13	L8-L9 202
			134		
R10	60	50		29	
			163		
-	-	-		-	L9-L10 197
R12	65	48		40	
			160		
L12	-	-			
			(120)		
R13	67	50		39	R12-R13 (248)
			158		
MEANS	**68.5**	**49.1**	**148**	**18.2**	**216.9**
			[L-R 138.2] [R-L 156.9]		
STANDARD DEVIATION **			**9.36**		**16.48**

* All measurements in centimeters. ** Calculated for trackway segment L2-L10.

As done with the theropod trackway we compared mean step length with maximum and minimum values and derived differences between 9 and 19% respectively (standard deviation = 9.36). These results can be compared with the differences between the mean stride length and maximum and minimum values (14.8 and 14.2% respectively; standard deviation = 16.48). The respective differences between maximum/mean stride and minimum/mean stride are 9.7 and 9.9% if the extreme values (in brackets in TABLE II) are omitted from the calculations. As discussed below, the greater variability in stride lengths relative to step lengths in the case of the sauropod trackway is, in part, a function of the difference in trackway width and corresponding pace angulation.

DISCUSSION

In addition to the trackway described by ISHIGAKI (1986), we know of at least seven other examples including a Lower Jurassic theropod from the eastern United States (LOCKLEY *et al.*, 1994, *in press*), an Upper Jurassic theropod trackway from Utah (ANONYMOUS, 1990), and Lower Cretaceous examples from Spain and Colorado (LOCKLEY *et al.*, 1994). In addition (WADE, 1989: fig. 8.5) illustrated a middle Cretaceous dinosaur trackway with alternating long and short steps. A "manus-only" Middle Jurassic sauropod trackway illustrated by ISHIGAKI (1989: fig. 9.3), from Morocco, also displays alternating long and short steps. Although Ishigaki interpreted this as an example of a swimming animal, we conclude that it represents the trackway of a sauropod walking on land (LOCKLEY & RICE, 1990). It is therefore evident that we now know of at least nine examples of dinosaur trackways with an alternating pattern of long and short steps. These span the Middle Jurassic through Middle Cretaceous and include examples attributed to quadrupeds (sauropods and ornithopods) and to large bipeds (ornithopods and theropods). Such observations suggest that such trackways may not be particularly rare. Further systematic searching, and careful measurement of step lengths in well-preserved trackways is likely to reveal additional examples. For example, FARLOW (*written commun.*, 1994, and unpublished data) indicates that additional examples of this type of trackway are quite common among theropod trackways in the Cretaceous of Texas. Our preliminary analyses of the Portuguese trackways, and the other cited examples, suggest that the mean short-long step ratios reported herein (80%) in the case of the Moroccan theropod and 87%, and 88% for the Portuguese examples are fairly typical values. However, having overlooked differences in step length of 10% or more in our studies, we suggest that the limping pattern may not always be obvious from visual inspection of a trackway. This underscores the need for careful measurement. With respect to the relationship between step lengths and

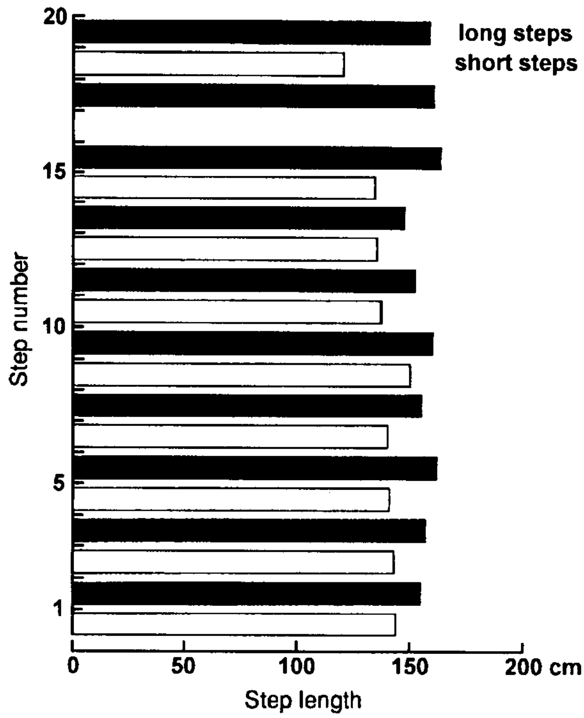

Fig. 2 - Chart showing alternating long and short steps of sauropod from track level 5.

stride lengths we note the following, based on the two different Portuguese examples of a biped and a quadruped. Trackways of bipeds are generally narrower and a stride closely approximates twice step length (mean step/mean stride = 51.5%; see TABLE I). By contrast the trackways of quadrupeds are wider, with stride lengths much less than two step lengths (mean step/mean stride = 68.2%; see TABLE II). Moreover, as quadrupeds have two pairs of limbs that can move independently to some degree, step lengths, pace angulations and individual stride lengths can be quite variable within any given trackway segment.

In the final analysis it is not possible to determine the reasons for the limping pattern observed in certain trackways. The Moroccan example illustrated by ISHIGAKI (1986) provides compelling evidence of an injury to the right foot. However, in all other examples there is no obvious evidence of foot injury based on track morphology. In such cases we are obliged to infer a multiplicity of possible causes including injury to any part of the leg or to possibly to other parts of the body. It is also possible that a congenital affliction caused the limp in known examples. Also, as speculated elsewhere (LOCKLEY, 1991), the trackmaker may simply have been favoring one foot because it temporarily had its body turned in a different direction from the trackway axis. This could have happened if the animal was looking one way awhile progressing in another direction. A bipedal dinosaur might also have favored one side if it was carrying something of substantial weight either in its jaws or with its front limbs. Or as FARLOW (*written commun.*, 1994) has suggested some animals may simply have been right or left footed. Such multiple working hypothesis cover a range of possibilities but are necessarily speculative. As is often the case in vertebrate ichnology we have evidence for a particular type of behavior, in this case limping locomotion (or alternating long and short steps), but cannot determine the reason for that behavior pattern.

CONCLUSIONS

1 - Dinosaur trackways with alternating long and short steps indicate limping behavior. In all but one example the cause of the limping behavior cannot be deduced from track morphology.

2 - At least nine examples of trackways attributable to limping dinosaurs are now known from the Middle Jurassic through Middle Cretaceous track record. Most of these examples are attributable to tridactyl bipeds; two are attributable to sauropods.

3 - Regardless of the difference in length between successive long and short steps, corresponding successive stride lengths are much more regular in length, especially in the trackways of bipeds. This step length/stride length relationship is more complex and variable in the trackways of quadrupeds in part because wider trackways result in larger step/stride ratios.

4 - Trackways of limping dinosaurs are not always obvious from visual inspection. However measurements of several consecutive steps clearly reveal a limping pattern in the examples recorded to date. Further careful analysis is needed to establish the frequency of occurence of such trackways.

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REFERENCES

ANONYMOUS (1991) - *Dinosaur footprints from the Morrison Formation, Moab Area Utah*. Univ. Colorado, Denver - Bureau of Land Management (Moab Office) brochure.

ISHIGAKI, S. (1986) - Dinosaur Footprints of the Atlas Mountains. *Nat. Study*, **32**: 6-9 (in Japanese).

ISHIGAKI, S. (1989) - Footprints of swimming sauropods from the Morocco *in* GILLETTE, D.D. & LOCKLEY, M.G. (Eds), *Dinosaur Tracks and Traces*, Cambridge Univ. Press, Cambridge, pp. 83-86.

LOCKLEY, M.G. (1991) - *Tracking Dinosaurs: A new look at an ancient world*. Cambridge Univ. Press, Cambridge, 238 pp.

LOCKLEY, M.G. & RICE, A. (1990) - Did *Brontosaurus* ever swim out to sea? Evidence from dinosaur tracks and other fossil footprints. *Ichnos*, **1**: 81-90.

LOCKLEY, M.G.; MEYER, C.A. & SANTOS, V.F. (1994) - Trackway evidence of a herd of juvenile sauropods from the Late Jurassic of Portugal. *Gaia (this volume)*.

LOCKLEY, M.G.; HUNT, A.; MORATALLA, J.J. & MATSUKAWA, M. (1994) - Limping Dinosaurs? Trackway evidence for abnormal gaits. *Ichnos*, **3**: 193-202.

RAMALHO, M.M. (1971) - Contribution a l'étude micropaléontologique et stratigraphique du Jurassique supérieur et du Crétacé inférieur des environs de Lisbonne (Portugal). *Mém. Serv. Geol. Portugal*, **19**, 212 pp.

WADE, M. (1989) - The stance of dinosaurs and the Cossack dancer syndrome *in* GILLETTE, D.D. & LOCKLEY, M.G. (Eds), *Dinosaur Tracks and Traces*, Cambridge Univ. Press, Cambridge, pp. 73-82.

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TRACKWAY EVIDENCE FOR A HERD OF JUVENILE SAUROPODS FROM THE LATE JURASSIC OF PORTUGAL[1]

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ABSTRACT: Studies of fossil footprints in Upper Jurassic carbonates at Lagosteiros Bay - Cabo Espichel, Sesimbra Region, Portugal, reveal the presence of multiple track-bearing levels with abundant trackways of sauropods. One level reveals good evidence for a herd of at least seven small sauropods that moved towards the southeast. All had similar foot sizes and wide-gauge trackways indicative of an age group of a single species. They were evidently accompanied by at least three larger individuals, also with wide-gauge trackways, that were also moving in approximately the same direction. This is the first convincing example of sauropod herd behavior reported from a European tracksite. It also provides the best known example of herding amongst juvenile sauropods. The Cabo Espichel trackway evidence for herding is compared with other tracksite evidence for brontosaur gregarious behavior and the implications for social behavior are considered.

RESUMO: Os estudos sobre pegadas de dinossáurios realizados no Jurássico superior da Baía dos Lagosteiros - Cabo Espichel (Sesimbra, Portugal), permitiram localizar várias camadas com abundantes pistas de saurópodes. Um dos níveis icnológicos possui um bom testemunho de uma manada de, pelo menos, sete saurópodes de pequenas dimensões que se moviam para sudeste. Todos os animais deixaram pegadas com dimensões idênticas e pistas largas ("wide-gauge"), o que indica um grupo etário de uma única espécie. Este grupo estava acompanhado por três indivíduos de grandes dimensões, que também deixaram pistas largas e se deslocavam aproximadamente na mesma direcção. Este é o primeiro exemplo convincente de comportamento gregário nos saurópodes, reconhecido numa jazida icnológica europeia, bem como o melhor testemunho conhecido de tal comportamento entre saurópodes juvenis. A jazida da Baía dos Lagosteiros, com o conjunto de pistas que evidenciam comportamento gregário, é comparável a outras jazidas e fornece importante informação com implicações no conhecimento do comportamento social dos dinossáurios.

INTRODUCTION AND PREVIOUS WORK

The present study is part of a cooperative study of dinosaur tracksites in Portugal aimed at revealing new insights into the paleobiology of Late Mesozoic dinosaurs. As previous work has shown, evidence of dinosaurs is quite common in Portugal (see GOMES, 1915-1916; ANTUNES, 1976, 1989 and SANTOS, 1990,

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for preliminary reports on tracksites and DANTAS, 1990, for review of skeletal evidence). Prior to the 1990's there had been no systematic attempt to study dinosaur tracksites in Portugal. However, in the wake of the so called "Dinosaur Footprint Renaissance" (LOCKLEY & GILLETTE, 1987; LOCKLEY, 1991a), there has been growing interest in dinosaur ichnology around the world, and a corresponding increase in publications in this field (LOCKLEY, 1991b; THULBORN, 1990). For example the authors are currently engaged in a systematic survey of dinosaur tracksites in Portugal (SANTOS, 1990), and have now published preliminary reports and new interpretations on a number of sites (see SANTOS *et al.*, 1992; LOCKLEY *et al.*, 1992b; LOCKLEY & SANTOS, 1993; DANTAS *et al.*, 1994; MEYER *et al.*, 1994; LOCKLEY *et al.*, 1994a, b and this paper). Taken together, this new spate of publications on Portuguese dinosaur ichnology indicates that the late Mesozoic, in particular the Late Jurassic carbonates of the Sesimbra region, are a particularly fruitful area for research. To date we have reported on the first good examples of Late Jurassic brontosaur tracks with well-preserved manus and pes digit impressions, what is probably the smallest sauropod trackway in Europe (smallest individual sauropod trackmaker), evidence of a limping sauropod and the first european examples of manus dominated sauropod trackways (see references cited above). The purpose of this paper is therefore to report on another new tracksite that provides compelling evidence for a herd of juvenile brontosaurs.

GEOLOGY AND STUDY METHODS

Between the autumn of 1992 and the summer of 1993 we conducted field work in the Sesimbra region to determine the extent of dinosaur track-bearing horizons in the Late Jurassic carbonates of this region. Maps and preliminary results from the Avelino tracksite (LOCKLEY & SANTOS, 1993) and the Zambujal quarry site (LOCKLEY *et al.*, 1992b) have already been published, indicating a rich pre-Portlandian (Kimmeridgian) track record in this area. The focus of this study however, is the Portlandian track-bearing deposits that crop out on the south side of Lagosteiros Bay below the monastery at Cabo Espichel.

We measured the stratigraphic section in this area, and determined that there were at least eight track-bearing levels in this sequence (Fig. 1). The succession consists of shallow water carbonates assigned to the Upper Portlandian or Portlandian B (RAMALHO, 1971, 1988). ANTUNES (1976) published a photograph of sauropod tracks that are easily visible just above the high tide line on what we now refer to as level 5 (see MEYER *et al.*, 1994: fig. 2). These are the tracks that have been referred to as "Pegadas de Mula" (ANTUNES, 1976; SANTOS, 1990; SANTOS *et al.*, 1992; LOCKLEY *et al.*, 1994a). However, prior to this study, no other tracks had been documented at any other levels.

We herein report on our preliminary efforts to map and document trackways at level number three (Fig. 1-3). Due to the very extensive, uncovered or "clean" and steeply-dipping bedding planes, the cliffs at Cabo Espichel present an excellent opportunity to see well-exposed trackways. In our preliminary reconaissance we scanned the cliffs with binoculars then photographed the outcrops to obtain enlarged photographs. This revealed an abundance of trackways, but it was not possible to identify the trackway types, their orientations or detailed trackway parameters from such long-distance surveys. Thus we had to climb the cliffs to map and measure the trackways on the outcrop.

The inclination of the cliffs at 40° or more is such that they are difficult to ascend safely. An experienced mountaineer could probably climb them without ropes, but this is not recommended. In order to work safely, and for prolonged periods of time, we ascended the cliffs with ropes and secured climbing bolts every 25 m. In this position we were secure, though not protected from the danger of falling rocks dislodged by wind, seagulls, curious spectators and tourists looking down from above. We used a tape measure, laid out directly up and down dip, as a base line or transect and mapped in at least six consecutive steps in the area where each trackway crossed the transect line. We also obtained measurements of footprint size, step and stride length and trackway width, for all trackways except number 1, which was difficult to access safely. Subsequently with enlarged photographs we were able to fill in the remaining sequence of steps in each trackway and complete an accurate scale map (Fig. 2). The two large sauropod trackways and the theropod trackway exposed on the same surface at the bottom of the cliff were also mapped, but without the need for safety ropes.

RESULTS

We recorded details of the carbonate lithology and fossil content at all levels in the section, including track-level three. These details will be published elsewhere, and are summarized only briefly herein. The track bed is rich in the remains of invertebrates including foraminifera, bivalves and gastropods. We also recovered isolated turtle bones attributable to the Plesiochelydae. The surface and upper part of the track bed also exhibits extensive invertebrate bioturbation (cf. *Thalassinoides*).

The results of our mapping indicate that at least twelve trackways are preserved on the surface of track bed three (Fig. 2-3). Of these eleven are those of sauropods and one is attributed to a tridactyl biped, probably a theropod. We numbered the trackways from the top of the exposure (the south) down the

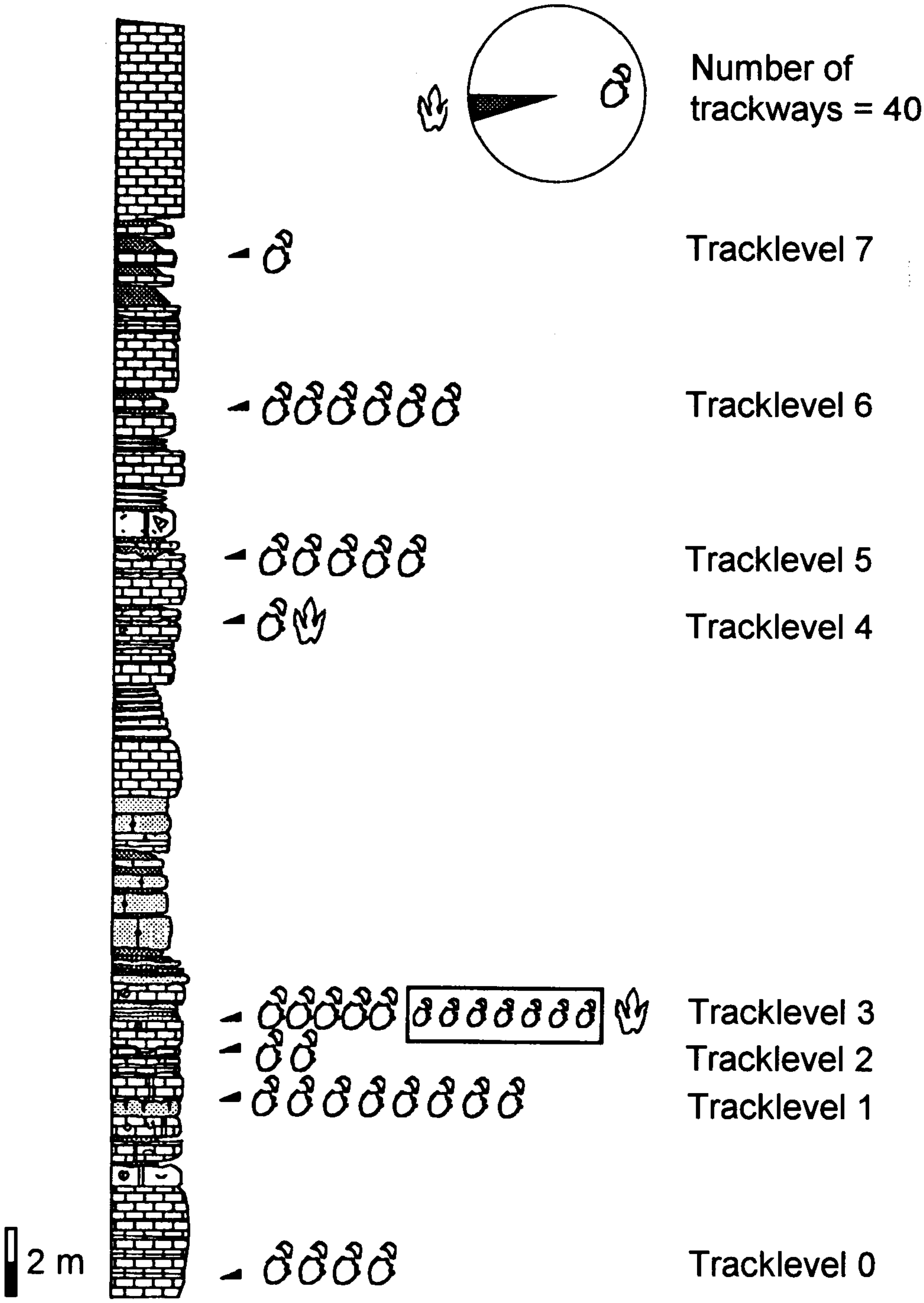

Fig. 1 - Stratigraphic section of Portlandian rocks on the south side of Lagosteiros Bay, showing track-bearing levels discussed in text.

cliff (to the north). Trackways 1-7 represent small individuals with pes lengths between 38 cm and 46 cm, and trackways 8, 10 and 11 represent larger individuals with pes lengths between 70 cm and 73 cm (TABLE I). Trackway 9 represents a manus-only trackway of a large sauropod in which only the right manus is well preserved (shown in black in Fig. 2). Trackway 12 represents a theropod dinosaur with a footprint length of 42 cm and width of 35 cm.

To determine the sauropod trackway gauge, we measured the distance between the inside margins of the pes tracks on all trackways except numbers 1 and 9. Our results clearly show that all the sauropod trackways on this surface have relatively wide-gauge

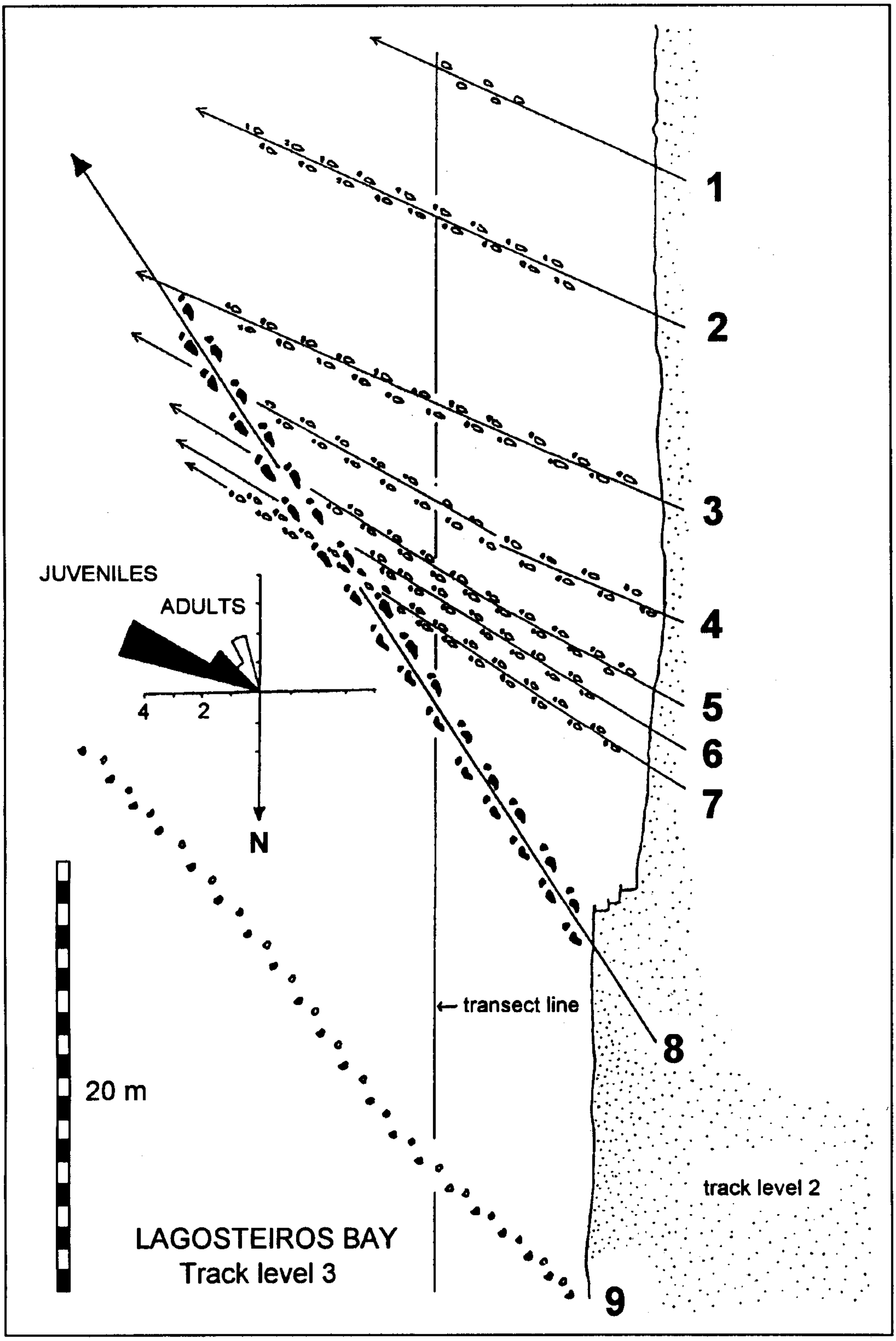

Fig. 2 - Map of track-bearing bedding plane number 3 exposed on upper part of cliff, south side of Lagosteiros Bay. Trackways of small brontosaurs numbered 1-7; trackways of large brontosaurs numbered 8-11 (see Fig. 3 for Nº 10 and 11). Trackway Nº 9 is dominated by right manus tracks.

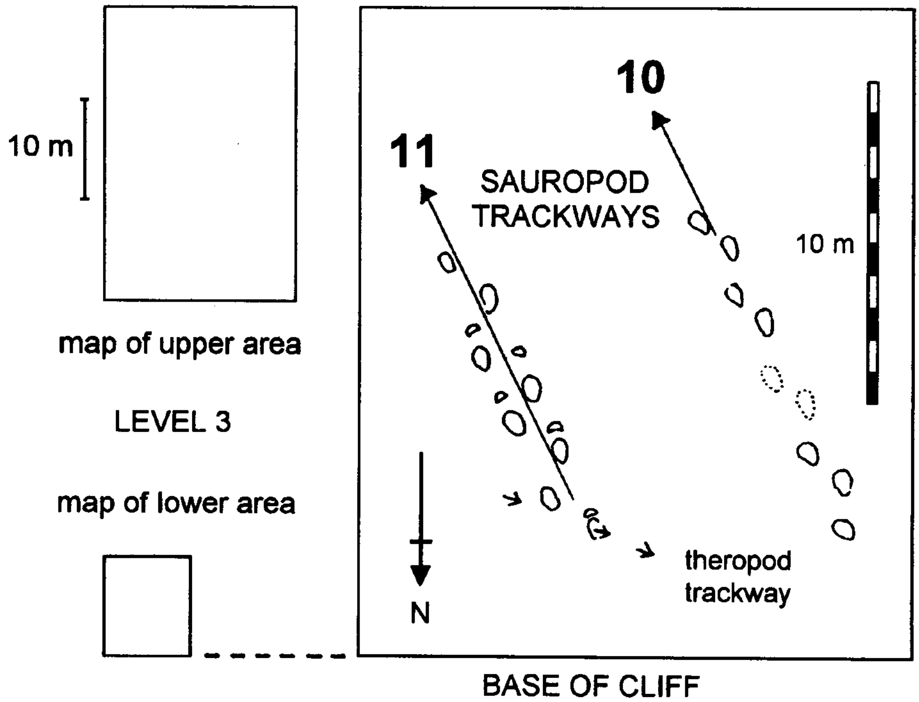

Fig. 3 - Map of track-bearing bedding plane Nº 3 exposed on lower part of cliff, south side of Lagosteiros Bay. Note orientation of sauropod trackways in relation to those recorded on map of upper area (Fig. 2). Both mapped areas presented with the same orientation.

TABLE I
Trackway measurements for track bed 3, Lagosteiros Bay (Upper Jurassic).

	TRACKWAY Nº	PES LENGTH	PES WIDTH	STRIDE	GAUGE*	SPEED $m.s^{-1}$
Small Brontosaurs (1-7)	1	-	-	-	wide	-
	2	46	30	210	42	1.32
	3	38	25	190	45	1.39
	4	40	28	182	54	1.21
	5	42	25	200	28	1.35
	6	45	30	175	42	1.00
	7	40	30	170	35	0.95
Large Brontosaurs (8-11)	8	70	55	230	(45)	0.93
	9	-	-	200	-	-
	10	70	45	260	-	1.15
	11	73	44	265	50	1.45
Theropod		42	35			

All measurements in cm. Speed (v) calculated using: $v = 0.25g^{0.5}.\lambda^{1.67}.h^{-1.17}$; where g - gravitational acceleration, λ - stride length and h - hip height (estimated as 4 x footprint length). (*) Distance between inside margin of hind footprints, measured perpendicular to the trackway axis, see text for details.

trackways (*sensu* FARLOW, 1992; MEYER *et al.*, 1994: fig. 4). In addition we measured trackway orientations and found that the small trackmakers (1-7) were heading towards the east south east (ESE) and the larger ones, 8, 10 and 11 were progressing towards the southeast (SE) (Fig. 2-3). The manus dominated trackway indicates an animal moving in the opposite direction towards the northwest (NW). We also calculated the speed of the sauropods using the formula of ALEXANDER (1976), see TABLE I. The results show that the small brontosaurs were travelling at between 0.95 and 1.39 $m.s^{-1}$ (=3.4-5.0 $km.h^{-1}$) and the large ones at 0.93-1.45 $m.s^{-1}$ (=3.3-5.2 $km.h^{-1}$). These are typical walking speeds for sauropods (LOCKLEY, 1987; THULBORN, 1990), and suggest no significant difference in velocities of the small and large individuals.

INTERPRETATION OF TRACKWAYS

It is clear from the trackway maps (Fig. 2-3) that there is a strong preferred orientation for the small trackmakers (between 114 and 122°) and for the large trackmakers (between 145 and 155° for numbers 8, 10 and 11). This suggests a small herd or group of subadult or juvenile individuals moving purposefully together in the same direction (Fig. 4), and a smaller number of larger (adult) individuals moving in the same general direction, but with their own distinct orientation that was slightly oblique (about 30°) to the direction of travel of the smaller group. It seems highly unlikely that the seven small trackways heading ESE, or the three large trackways heading SE, bear no relationship to one another. On the contrary, evidence from other tracksites suggests that sauropods and other dinosaurs sometimes travelled in distinctive size groups, each with distinctive preferred directions. Such evidence argues against the trackways representing isolated individuals that passed by at different times. The NW orientation (towards 320°) of the manus dominated trackway, and the obviously different mode of preservation, can be used to suggest that the trackmaker passed by at a different time from all the other sauropods, when substrate conditions were different.

DISCUSSION

Large samples of sauropod trackways are now known from several sites around the world including Texas (BIRD, 1944), Colorado (LOCKLEY, HOUCK & PRINCE, 1986; LOCKLEY & RICE, 1990), South Korea (LIM, YANG & LOCKLEY, 1989; LIM *et al.*, 1994), Morocco (ISHIGAKI, 1989), Portugal (LOCKLEY & SANTOS, 1993) and Switzerland (MEYER, 1990, 1993). In the former two examples, Texas and Colorado, parallel trackways provide compelling evidence for gregarious behavior among the trackmakers. The Texas examples, from the Paluxy River and Davenport Ranch sites respectively, were the first reported trackway evidence for herds of at least 12 and 23 sauropods (BIRD, 1941, 1944). These reports have become classic examples of trackway evidence for social behavior that have been cited on many occasions (OSTROM, 1972; LOCKLEY, 1987, 1989, 1991b; THULBORN, 1990). The Colorado site, known as the Purgatoire Valley dinosaur tracksite, has revealed evidence of at least twelve parallel trackways including five very well-preserved examples made by subadult sauropods that were very similar in size. The Korean sites have yielded a large sample that includes many of the smallest known sauropod trackways, but no good evidence of herding.

Comparisons of the size of the Texas and Colorado trackmakers with those from Portugal reveal the following. Trackways from Davenport Ranch, Texas, average 53 cm long (range 35-78 cm) with no obvious clustering of larger and smaller animals. Tracks from the Purgatoire Valley site, Colorado, are also variable in size, but include one obvious grouping of 5 parallel trackways with an average foot length of 57 cm (range 52-60 cm). By contrast the six measured, small sauropod trackways from Lagosteiros Bay, Portugal, show an average length of 42 cm (range 38-46 cm; TABLE I). Thus the Portuguese tracks are only 79 and 74% respectively of the size of the tracks from Texas and Colorado, and are thus the best evidence available for small brontosaurs travelling in groups.

A full review of dinosaur tracksites that reveal evidence of gregarious behavior is outside the scope of this paper, so we have mainly confined ourselves to a discussion of sauropod tracksites. However it is worth mentioning that a number of Cretaceous ornithopod tracksites have been described where there is evidence of gregarious behavior. At the Mosquero Creek site in New Mexico for example trackways indicate that small ornithopods were travelling in one direction, and large ones in the opposite direction (LOCKLEY *et al.*, 1992a; LOCKLEY, MATSUKAWA & HUNT, 1993). This strongly suggest that trackways allow ichnologists to identify various size or age groups, particularly in the large trackway samples that are attributable to gregarious dinosaur species (LOCKLEY, 1994). Based on tentative age estimates recently proposed by LOCKLEY (1994) the Portuguese sauropod trackmakers would probably have been no more than one to two years old.

We note that the dinosaur track assemblages (ichnocoenoses) in the Upper Jurassic carbonates of the Sesimbra region are heavily dominated by the trackways of sauropods. This means that they can be assigned to the *Brontopodus* ichnofacies (*sensu* LOCKLEY, HUNT & MEYER, 1994; LOCKLEY & HUNT, *in press*). This ichnofacies is particularly well represented in the Upper Jurassic of Portugal, the Upper Jurassic of Switzerland (MEYER, 1993) and the Lower Cretaceous of Texas.

Fig. 4 - Reconstruction of a herd of seven juvenile sauropods travelling east-south-east. Based on trackway configurations shown in Figure 2. Artwork by Paul Koroshetz.

CONCLUSIONS

1 - Portlandian dinosaur trackways from the trackbed designated as number 3 at Lagosteiros Bay provide the first compelling evidence of gregarious sauropods so far reported from Europe.

2 - These gregarious sauropods were evidently travelling in two sub groups consisting of small animals (foot length 38-46 cm) and larger animals (foot length 70-73 cm). But all were travelling towards the southeast. No other trackway evidence for a gregarious group of brontosaurs is currently known in which the individuals consistently have such small foot sizes.

3 - The abundance of sauropod tracks in shallow water to marginal marine carbonates is typical of the *Brontopodus* ichnofacies (*sensu* LOCKLEY, HUNT & MEYER, 1994).

4 - Trackbed 3 also provides further evidence that manus only sauropod trackways are common in carbonate deposits.

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REFERENCES

ALEXANDER, R.M. (1976) - Estimates of speeds of dinosaurs. *Nature*, **261**: 129-130.

ANTUNES, M.T. (1976) - Dinossáurios Eocretácicos de Lagosteiros. *Ciências da Terra*, **1**, 35 pp.

ANTUNES, M.T. (1989) - Dinossáurios em Sesimbra e Zambujal - episódios de há cerca de 140 milhões de anos. *Sesimbra Cultural*, **0**: 12-14.

BIRD, R.T. (1941) - A dinosaur walks into the museum. *Natural History*, **47**: 74-81.

BIRD, R.T. (1944) - Did *Brontosaurus* ever walk on land? *Natural History*, **53**(2): 60-67.

DANTAS, P. (1990) - Dinossáurios de Portugal. *Gaia*, **2**: 17-26.

DANTAS, P.; SANTOS, V.F.; LOCKLEY, M.G. & MEYER, C.A. (1994) - Footprint evidence for limping dinosaurs from the Upper Jurassic of Portugal. *Gaia* (*this volume*).

FARLOW, J.O. (1992) - Sauropod Tracks and trackmakers: integrating the ichnological and skeletal records. *Zubia*, **10**: 89-138.

GOMES, J.P. (1915-1916) - Descoberta de rastos de sáurios gigantescos no Jurássico do Cabo Mondego. *Comun. Com. Serv. Geol. Portugal*, **11**: 132-134 (*in* "Manuscritos de Jacinto Pedro Gomes"). Publicação póstuma.

ISHIGAKI, S. (1989) - Footprints of swimming sauropods from Morocco *in* GILLETTE, D.D. & LOCKLEY, M.G. (Eds), *Dinosaur Tracks and Traces*, Cambridge Univ. Press, Cambridge, pp. 83-86.

LIM, S.-K.; YANG, S.-Y. & LOCKLEY, M.G. (1989) - Large Dinosaur Footprint assemblages from the Cretaceous Jindong Formation of Southern Korea *in* GILLETTE, D.D. & LOCKLEY, M.G. (Eds), *Dinosaur Tracks and Traces*, Cambridge University Press, Cambridge, pp. 333-336.

LIM, S.-K.; LOCKLEY, M.G.; YANG, S.-Y.; FLEMING, R.F. & HOUCK, K. (1994) - A preliminary report on sauropod tracksites from the Cretaceous of Korea. *Gaia* (*this volume*).

LOCKLEY, M. G. (1987) - Dinosaur Trackways *in* CZERKAS, S.J. & OLSEN, E.C. (Eds), *Dinosaur Past and Present*, Los Angeles County Nat. Hist. Mus. Symp., Los Angeles, pp. 80-95.

LOCKLEY, M.G. (1989) - Tracks and Traces: New Perspectives on Dinosaurian Behavior, Ecology and Biogeography *in* PADIAN, K. & CHURE, D.J. (Eds), *The Age of Dinosaurs, Short courses in Paleontology*, **2**, Paleontol. Soc., Knoxville, Tenn., pp. 134-145.

LOCKLEY, M.G. (1991a) - The Dinosaur Footprint Renaissance. *Modern Geol.*, **16**: 139-160.

LOCKLEY, M.G. (1991b) - *Tracking Dinosaurs: a new look at an ancient world.* Cambridge Univ. Press, Cambridge, 238 pp.

LOCKLEY, M.G. (1994) - Dinosaur ontogeny and population structure: interpretations and speculations based on footprints *in* CARPENTER, K.; HIRSCH, K. & HORNER, J. (Eds), *Dinosaur Eggs and Babies*, Cambridge Univ. Press, Cambridge, pp. 347-365.

LOCKLEY, M.G.; FLEMING, R.F.; YANG, S.-Y. & LIM, S.-K. (1991) - The distribution of dinosaur and bird tracks in the Jindong Formation of South Korea: implications for paleoecology *in Intern. Symp. on Origin, Sedimentation and Tectonics of Late Mesozoic to Early Cenozoic sedimentary basins at the eastern Margin of the Asian Continent*, Kyushu University, Fukuoka, Japan, Aug. 25-30, p. 61.

LOCKLEY, M.G. & GILLETTE, D.D. (1987) - Dinosaur Tracks Symposium signals a renaissance in vertebrate ichnology. *Paleobiology*, **13**: 246-252.

LOCKLEY, M.G.; HOUCK, K.J. & PRINCE, N.K. (1986) - North America's largest dinosaur trackway site: implications for Morrison Formation paleoecology. *Bull. Geol. Soc. Am.*, **97**: 1163-1176.

LOCKLEY, M.G. & HUNT, A.P. (*in press*) - *Dinosaur Tracks and other fossil footprints from the western United States.* Columbia Univ. Press.

LOCKLEY, M.G.; HUNT, A.P.; HOLBROOCK, J.; MATSUKAWA, M. & MEYER, C.A. (1992a) - The dinosaur freeway: a preliminary report on the Cretaceous Megatracksite, Dakota Group, Rocky Mountain Front Range and Highplains, Colorado Oklahoma and New Mexico *in* FLORES, R. (Ed.), *Mesozoic of the Western Interior*, SEPM Midyear Mtg. Fieldtrip Guidebook, pp. 39-54.

LOCKLEY, M.G.; HUNT, A.P. & MEYER, C.A. (1994) - Vertebrate tracks and the Ichnofacies Concept: implications for paleoecology and palichnostratigraphy *in* DONOVAN, S. (Ed.), *The Paleobiology of Trace Fossils*, Wiley & Sons, New York, pp. 241-268.

LOCKLEY, M.G.; MATSUKAWA, M. & HUNT, A. (1993) - *Tracking Dinosaurs: New interpretations based on footprints. An Exhibit Guidebook.* Univ. Colorado, Denver, 68 pp.

LOCKLEY, M.G.; NOVIKOV, V.; SANTOS, V.F.; NESSOV, L.A. & FORNEY, G, (1994a) - "Pegadas de Mula": an explanation for the occurrence of Mesozoic traces that resemble mule tracks. *Ichnos*, **3**: 125-133.

LOCKLEY, M.G.; PITTMAN, J.G.; MEYER, C.A. & SANTOS, V.F. (1994b) - On the common occurrence of manus-dominated sauropod trackways in Mesozoic carbonates. *Gaia* (*this volume*).

LOCKLEY, M.G. & RICE, A. (1990) - Did "*Brontosaurus*" ever swim out to sea?: evidence from brontosaur and other dinosaur footprints. *Ichnos*, **1**: 81-90.

LOCKLEY, M.G. & SANTOS, V.F. (1993) - A preliminary report on sauropod trackways from the Avelino Site, Sesimbra Region, Upper Jurassic, Portugal. *Gaia*, **6**: 38-42.

LOCKLEY, M.G.; SANTOS, V.F.; RAMALHO, M.M. & GALOPIM DE CARVALHO, A.M. (1992b) - Novas jazidas de pegadas de dinosáurios no Jurássico superior de Sesimbra (Portugal). *Gaia*, **5**: 40-43.

MEYER, C.A. (1990) - Sauropod tracks from the Upper Jurassic Reuchenette Formation (Kimmeridgian: Lommiswil, Kt. Solothurn) of Northern Switzerland. *Eclogae Geol. Helv.*, **83**: 389-397.

MEYER, C.A. (1993) - A sauropod dinosaur megatracksite from the Late Jurassic of Northern Switzerland. *Ichnos*, **3**: 29-38.

MEYER, C.A.; LOCKLEY, M.G.; ROBINSON, J.W. & SANTOS, V.F. (1994) - A comparison of well-preserved sauropod tracks from the Late Jurassic of Portugal and the Western United States: evidence and implications. *Gaia* (*this volume*).

OSTROM, J.H. (1972) - Were some dinosaurs gregarious? *Palaeogeog., Palaeoclimatol., Palaeoecol.*, **11**: 287-301.

RAMALHO, M.M. (1971) - Contribution à l'étude micropaléontologique et stratigraphique du Jurassique supérieur et du Crétacé inférieur des environs de Lisbonne (Portugal). *Mem. Serv. Geol. Portugal*, **19**, 218 pp.

RAMALHO, M.M. (1988) - Microfaciès des couches à pistes de dinosaures au Portugal - considérations paléoécologiques. *Rev. Micropaleontol.*, **30**: 267-275.

SANTOS, V.F. (1990) - Icnofósseis de dinossáurios de Portugal. Alguns aspectos paleoecológicos. *Seminário Científico, Fac. Ciências, Univ. Lisboa*, 36 pp. (*unpublished*).

SANTOS, V.F.; LOCKLEY, M.G.; MORATALLA, J.J. & GALOPIM DE CARVALHO, A.M. (1992) - The longest dinosaur trackway in the world?: interpretations of Cretaceous footprints from Carenque, near Lisbon, Portugal. *Gaia*, **5**: 18-27.

THULBORN, R.A. (1990) - *Dinosaur Tracks*. Chapman Hall, London, 410 pp.

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ON THE COMMON OCCURRENCE OF MANUS-DOMINATED SAUROPOD TRACKWAYS IN MESOZOIC CARBONATES[1]

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ABSTRACT: Ongoing studies of sauropod track-bearing beds in the Upper Jurassic of Portugal, and elsewhere around the world, reveals that incomplete, sauropod trackways dominated by manus impressions are quite common. They have now been recorded at a total of six stratigraphic levels, in Portugal, and at 12 sites worldwide. Such trackways may be shallow underprints associated with smooth surfaces and relatively firm ground, or deeper impressions associated with irregular, soft ground surfaces. Incomplete trackways associated with softer, irregular surfaces, may also be associated with other, complete sauropod trackways. This indicates that differential timing of trackmaking episodes on a given surface contributes to the differential preservation we see in the fossil record. In some instances manus-dominated sauropod trackways, on irregular surfaces, consist primarily of a set of manus impressions representing only the right or left front footprints. Such observations reinforce the notion that it is important to understand substrate and preservation conditions before interpreting trackway morphology, or drawing conclusions about trackway behavior. A brief global survey of examples of manus-dominated sauropod trackways reveals that good examples have been reported from the Jurassic of Morocco and Portugal, and from the Cretaceous of Texas. We suggest that a report of an unusual trackway from Texas, attributed to a giant ornithopod, might alternatively be considered a possible example of a manus-dominated sauropod trackway.

RESUMO: Os estudos que se estão a realizar nas camadas com icnitos do Jurássico superior de Portugal e em vários locais no mundo têm demonstrado que as pistas incompletas de saurópodes, constituídas dominantemente por impressões dos autópodes anteriores, não são raras no registo fóssil. Em Portugal foram observadas cinco pistas pertencentes a cinco níveis estratigráficos, sendo conhecidos em todo o mundo onze exemplos. Estas pistas poderão ser subimpressões associadas a superfícies duras e regulares ou impressões profundas associadas a superfícies brandas e irregulares. Pistas incompletas em camadas brandas podem aparecer associadas a pistas de saurópodes completas. Isto

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indica que os animais podem ter passado num determinado local em tempos diferentes, contribuindo para uma preservação diferencial, a qual é observada no registo fóssil. Algumas pistas de saurópodes incompletas, observadas em camadas brandas irregulares, são constituídas predominantemente por impressões do autópode anterior esquerdo ou direito. Estes casos vêm chamar a atenção para a necessidade de se conhecer o substrato e as condições de preservação antes de se tentar interpretar a morfologia dos icnitos ou de se esboçar conclusões sobre comportamento. Bons exemplos de pistas constituídas principalmente por impressões de autópodes anteriores foram descobertos no Jurássico superior de Marrocos e de Portugal e no Cretácico do Texas (EUA). Sugerimos neste artigo que a estranha pista do Texas, atribuída a um ornitópode gigante, poderá ser um possível exemplo de pista incompleta de saurópode, onde se observam apenas as impressões dianteiras.

INTRODUCTION

The first manus-dominated sauropod trackway was reported by Roland Bird in 1944, and attributed to the activity of a partly bouyant, swimming animal that touched the substrate mainly with its front feet (BIRD, 1944, 1985). This interpretation, which became widely accepted, was originally influenced by the erroneous hypothesis that sauropods were primarily aquatic animals. It also lead to the erroneous assumption that incomplete trackways were indicative of swimming behavior. The result was circular reasoning and the development of a myth that has persisted in the paleontological literature for half a century. As a result, subsequent discoveries of manus-dominated sauropod trackways (ISHIGAKI, 1989) and other incomplete dinosaur trackways were also interpreted as the result of the activity of swimming trackmakers (see LOCKLEY, 1991, for review). It was not until very recently that LOCKLEY & RICE (1990) demonstrated that the trackway described by BIRD (1944) consisted of undertracks, a conclusion supported by PITTMAN (1990, 1992) who found an additional pes underprint in the trackway described by BIRD (1944), Figure 1 herein. Despite this new interpretation, several authors of recent books on dinosaurs (*e.g.* CZERKAS & CZERKAS, 1990; NORMAN, 1991; THULBORN, 1990) have continued to adhere to the original interpretation of BIRD (1944), possibly because they were unaware of the undertracks evidence.

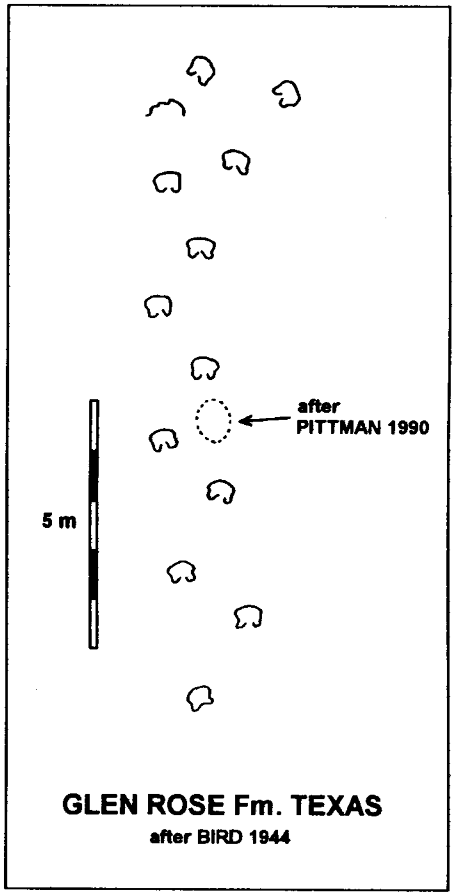

Fig. 1 - Manus dominated trackway illustrated by BIRD (1944). Note pes track (dotted line) discovered by PITTMAN (1990).

Recent work on sauropod trackways at a number of sites southwest of Lisbon, Portugal (LOCKLEY *et al.*, 1992; LOCKLEY & SANTOS, 1993) reveals that manus-dominated trackways are quite common in Late Jurassic carbonate facies. As summarized herein, and in other papers in this volume, further work in this region has revealed several additional examples. The purpose of this paper is therefore to summarize all known examples and to discuss the implications of the available evidence.

EXAMPLES OF MANUS-DOMINATED AND MANUS-ONLY SAUROPOD TRACKWAYS

We describe known examples of manus-dominated and manus-only trackways, in ascending stratigraphic order, discuss the trackway configurations, and, where appropriate, the associated sedimentological evidence. A summary of the available data is given in TABLE I.

MIDDLE JURASSIC

Middle Jurassic manus dominated sauropod trackways from Morroco were described by ISHIGAKI (1989) and attributed to swimming sauropods. In this paper, he illustrated four examples, two of which can be considered manus-only trackways. The other two

TABLE I
The distribution of manus-dominated (MD) and manus-only (MO) sauropod trackways in the geologic record.

AGE	LOCALITY	SEDIMENTARY FACIES	NUMBER AND TYPE	MD/MO
Lower Cretaceous	Texas	Carbonate platform	3*	(2MD + 1MO)
Upper Jurassic (Kim)	Portugal	Carbonate platform	1	MD
Upper Jurassic (Kim)	Portugal	Carbonate platform	1	MD
Upper Jurassic (Port)	Portugal	Carbonate platform	3	(1MD + 2MO)
Middle Jurassic	Morocco	Sebkha	4	(2MD + 2MO)
Middle Jurassic	Portugal	Carbonate platform	5	MO
TOTALS				**(7MD + 10MO)**

Abbreviations: Kim - Kimmeridgian; Port - Portlandian. (*) One of these examples may alternatively be attributed to a large ornithopod.

examples show partial pes tracks that consist of the anterior portion of the hind footprint, in some cases comprising isolated toe prints, and so should be described as manus-dominated trackways. As summarized by ISHIGAKI (1989) and LOCKLEY & RICE (1990) the tracks are found in red calcareous mudcracked, mudstones interpreted as a lagoonal or sebkha environment, representing semi-arid conditions.

After this paper was written a new Middle Jurassic track site was discovered in Portugal that reveals at least five manus only trackways in a carbonate substrate (TABLE I and SANTOS *et al.*, this volume).

LATE JURASSIC

Late Jurassic manus-dominated and manus-only trackways are now known from at least five different stratigraphic levels in the shallow water, carbonate platform sequences from southwest of Lisbon (Sesimbra region, Portugal). Two examples from Kimmeridgian deposits, at the Zambujal and Avelino sites respectively, have already been illustrated and described briefly (LOCKLEY *et al.*, 1992; LOCKLEY & SANTOS, 1993). The latter example is associated with a very smooth bedding plane surface somewhat similar to the two undertrack-bearing surfaces described below from the Cretaceous of Texas.

The other three examples are from three different stratigraphic levels in the Portlandian limestones of Lagosteiros Bay near Cabo Espichel. The track beds at these stratigraphic levels are designated 0 through 7 (LOCKLEY, MEYER & SANTOS, 1994: fig. 1), with levels 0,3 and 5 each revealing a single example of relatively deep manus-dominated or manus-only trackways associated with irregular burrowed surfaces in wackestone lithologies. The trackway from level 0 is illustrated here for the first time (Fig. 2), and the trackways from levels 3 and 5 respectively are illustrated in LOCKLEY, MEYER & SANTOS (1994: fig. 2) and MEYER *et al.*,(1994: fig. 2). All three examples are interesting because they reveal much bet-

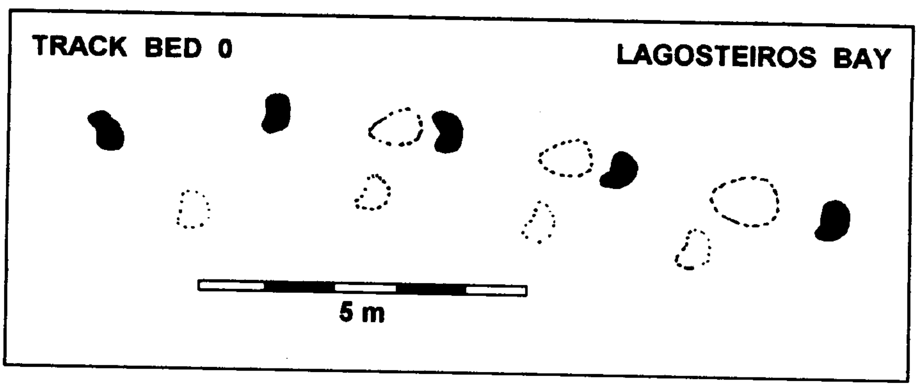

Fig. 2 - Manus dominated trackway from trackbed 0 in Portlandian carbonate sequence at Cabo Espichel, Portugal. Clear tracks of left manus are shown in black.

ter preservation of tracks on one side of the trackway than the other, and they occur on surfaces with other trackways that are relatively complete, and well-preserved. For example the trackway in Track bed 0 (Fig. 2) reveals, in addition to manus impressions that are clearer than the pes footprints, tracks on the left side of the trackway that are more clearly visible than those on the right side. In the case of the manus-only trackway on Track bed 3, the tracks on the right side are more clearly visible than those on the left (LOCKLEY, MEYER & SANTOS, 1994: fig. 2), and in the case of Track bed 5, only the manus tracks from one side of the trackway are visible (MEYER *et al.*,1994: fig. 2). The presence of visible tracks only on one side of this latter trackway, and the difficult location on a cliff face, makes it difficult to determine which side is represented. Track beds 3 and 5 both also exhibit other relatively complete, well-preserved sauropod trackways.

LOWER CRETACEOUS

Lower Cretaceous manus dominated trackways from Texas include the famous example from the Mayan Ranch site, originally described by BIRD (1944), and subsequently illustrated by many other authors. The tracks are very shallow and associated with a very smooth bedding plane surface at the top of the Lower Glen Rose Formation. The lithology as described by PITTMAN (1989) is a micrite/mudstone.

The second, possible example of a manus-dominated sauropod trackway comes from the Guadalupe River site, in the same general geographical area and at the same stratigraphic level as the Mayan ranch site. "All tracks at this site are ghost prints" and there are "several sauropod trackways" at this site (PITTMAN, 1989: 147-148). Again the trackways are associated with a relatively smooth surface described as micrite/mudstone (*op. cit.*).

This trackway was originally described as an ornithopod trackway (PITTMAN, 1989, 1992) with three broad digital pes impressions and manus tracks comprising two separate impressions. In this interpretation the manus tracks were situated anterior to, and well outside, the pes tracks (Fig. 3A). While this interpretation may be correct, we propose an alternate possibility, and suggest that if the trackway is turned around, through 180°, to give an opposite sense of progression, it also conforms to the pattern of certain know manus-dominated sauropod trackways. The large impression could then be interpreted as the manus print, and the two smaller paired impressions could be the traces of the large pedal claws or unguals (presumably numbers I and II). In support of this alternate interpretation we note that, if the normal *Brontopodus* trackway pattern is superimposed on the Guadalupe trackway, it provides an almost perfect fit, including pace angulation values of about 110° (Fig. 3B-C). Moreover the pattern is similar to the configuration seen in parts of the Mayan Ranch trackway (Fig. 1), and Moroccan trackway B (ISHIGAKI, 1989: fig. 9.2) in showing isolated impressions of two (or three) pes digits posterior to the manus trace. We consider this sauropod interpretation more parsimonious than the alternate ornithopod trackway hypothesis, but note that it might not have been proposed, had it not become apparent that so many sauropod trackways are manus dominated or otherwise incomplete.

Some factors cast doubt on this alternate interpretation. For example, the pes imprints interpolated in the suggested reconstruction (Fig. 3B) are situated somewhat further from the mid line than in the type *Brontopodus*. We note here also that, regardless of which interpretation is preferred, there is a slight asymmetry to the trackway, with paired impressions on one side of the trackway being situated a little further (laterally) from the large impressions than those on the other side.

A final observation on this subject pertains to the subtle adjustment of paleoecological census data that results if the alternate sauropod interpretation is correct. It has already been established that ornithopod trackways are rare in carbonate ichnofacies worldwide, including the Glen Rose Formation of Texas. In fact the predominace of brontosaur tracks has lead to the definition of a *Brontopodus* ichnofacies (LOCKLEY, HUNT & MEYER, 1994) in which ornithopod tracks are at best very rare, and often completely absent, it could be argued that the proposed alternate interpretation is more consistent with this recently established ichnofacies model, and with the fact that other sauropod trackways occur at the Guadalupe site.

A third example of a manus only trackway from the Cretaceous of Texas was recently reported by PITTMAN (1992: 300) from the Blanco River site as follows: "Trackway #11 consists only of shallow manus impressions, from only one side - all three prints are from the right side or all three are from the left. Because no pes prints were observed, directional information could not be identified". This example is reminiscent of the example cited above from Track bed 5 at Lagosteiros Bay where it is not clear whether the tracks represent the right side or the left side.

DISCUSSION AND CONCLUSIONS

It is becoming clear that manus-dominated and manus-only sauropod trackways are quite common in carbonate platform facies assigned to the *Brontopodus* ichnofacies. They also occur in sebkha facies with associated carbonates. It is also clear that the phenomenon is, to a significant degree, controlled by preservational factors, rather than by the behavior of the trackmakers (LOCKLEY & RICE, 1990).

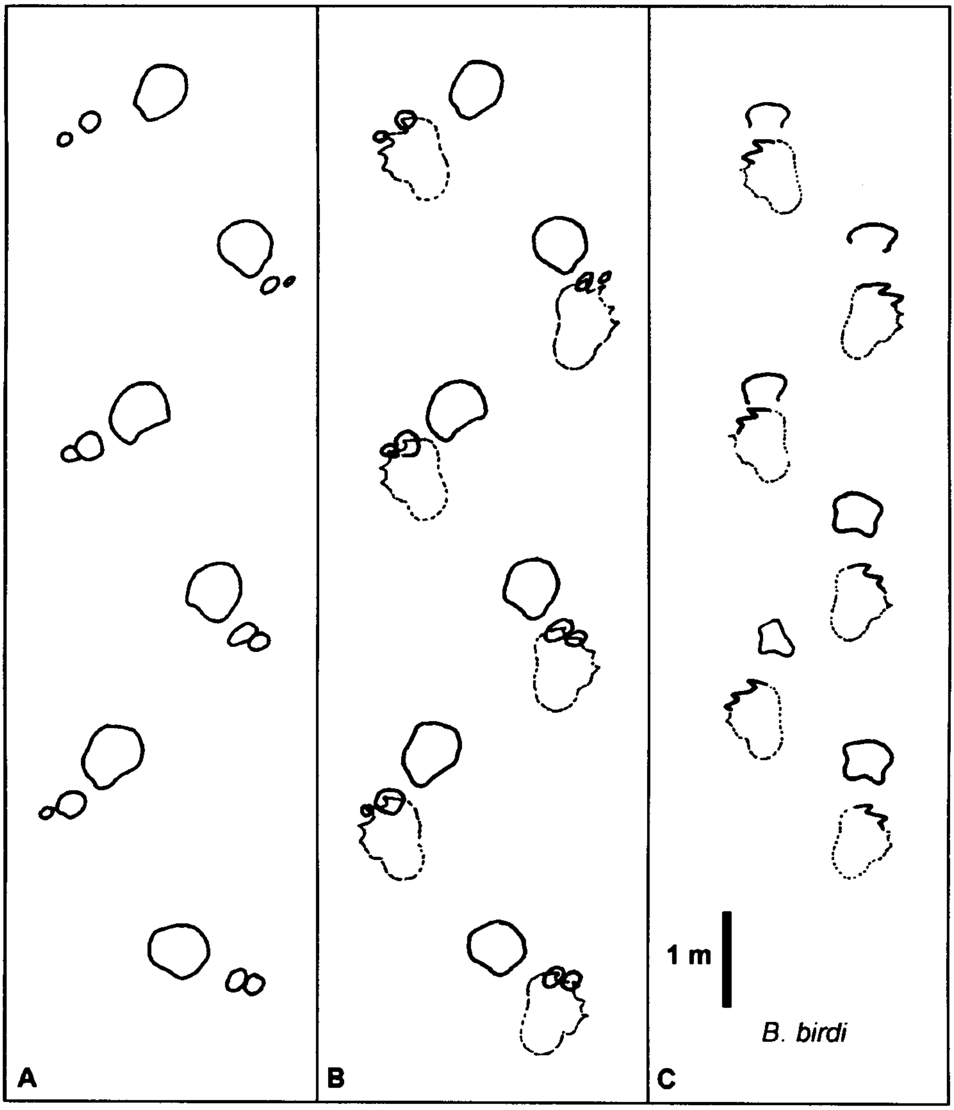

Fig. 3 - Comparison between A, possible trackway of large quadrupedal ornithopod (after PITTMAN, 1989, 1992), B, interpretation of same trackway as a manus-dominated sauropod trackway with opposite sense of direction and C, type trackway of *Brontopodus birdi* with manus and pes toe impressions emphasised (bold line).

Available evidence suggests that shallow manus-dominated trackways on smooth surfaces are clearly underprints transmitted through thin beds to firm underlayers. Incomplete manus-dominated or manus-only trackways associated with more irregular, burrowed surfaces are all relatively deep, with clear, relatively vertical margins. This implies that they were made in softer sediment, possibly penetrating through soft muddy layers into soft under layers. The known examples, in the Portlandian beds at Lagosteiros Bay, are associated with surfaces overlain by thin shaley beds. The presence of invertebrate bioturbation in these layers supports the conclusion that they were soft grounds. By contrast the former category of undertracks is associated with sediments that reveal much less extensive invertebrate bioturbation, and would have originally represented firmer ground. New discoveries, for example in the Middle Jurassic of Portugal, indicate considerable potential for further study.

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REFERENCES

BIRD, R.T. (1944) - Did *Brontosaurus* ever walk on land? *Nat. Hist.*, **53**(2): 60-67.

BIRD, R.T. (1985) - *Bones for Barnum Brown: Adventures of a Dinosaur Hunter*. Texas Christian Univ. Press, Fort Worth, 225 pp.

CZERKAS, S.J. & CZERKAS, S. (1990) - *Dinosaurs a global view*. Dragons World Press, Limpsfield, 247 pp.

ISHIGAKI, S. (1989) - Footprints of swimming sauropods from Morocco *in* GILLETTE, D.D. & LOCKLEY, M.G. (Eds), *Dinosaur Tracks and Traces*, Cambridge Univ. Press, Cambridge, pp. 83-86.

LOCKLEY, M.G. (1991) - *Tracking Dinosaurs: a new look at an ancient world*. Cambridge Univ. Press, Cambridge, 238 pp.

LOCKLEY, M.G. & RICE, A. (1990) - Did "*Brontosaurus*" ever swim out to sea?: evidence from brontosaur and other dinosaur footprints. *Ichnos*, **1**: 81-90.

LOCKLEY, M.G. & SANTOS, V.F. (1993) - A preliminary report on sauropod trackways from the Avelino Site, Sesimbra Region, Upper Jurassic, Portugal. *Gaia*, **6**: 38-42.

LOCKLEY, M.G.; HUNT, A.P. & MEYER, C.A. (1994) - Vertebrate tracks and the ichnofacies concept: implications for paleoecology and palichnostratigraphy *in* DONOVAN, S. (Ed.), *The Paleobiology of Trace Fossils*, Wiley & Sons, New York, pp. 241-268.

LOCKLEY, M.G.; MEYER, C.A. & SANTOS, V.F. (1994) - Trackway evidence for a herd of Juvenile sauropods from the Late Jurassic of Portugal. *Gaia* (*this volume*).

LOCKLEY, M.G.; SANTOS, V.F.; RAMALHO, M.M. & CARVALHO, A.M. GALOPIM DE (1992) - Novas jazidas de pegadas de dinossáurios no Jurássico superior de Sesimbra (Portugal). *Gaia*, **5**: 40-43.

MEYER, C.A.; LOCKLEY, M.G.; ROBINSON, J.W. & SANTOS, V.F. (1994) - A comparison of well-preserved sauropod tracks from the Late Jurassic of Portugal, and the Western United States: Evidence and implications. *Gaia* (*this volume*).

NORMAN, D. (1991) - *Dinosaur*. Prentice Hall, London, 192 pp.

PITTMAN, J.G. (1989) - Stratigraphy, Lithology, Depositional Environment, and Track type of Dinosaur Track-bearing Beds of the Gulf Coastal Plain *in* GILLETTE, D.D. & LOCKLEY, M.G. (Eds), *Dinosaur Tracks and Traces*, Cambridge Univ. Press, Cambridge, pp. 135-153.

PITTMAN, J.G. (1990) - Dinosaur Tracks and Trackbeds in the middle part of the Glen Rose Formation, Western Gulf Basin, USA. *Geol. Soc. Am., Field Trip Guide*, **8**: 47-83.

PITTMAN, J.G. (1992) - Stratigraphy and Vertebrate Ichnology of the Glen Rose Formation, Western Gulf Basin, USA. *Doctoral Thesis, Univ. Texas, Austin*, 726 pp. (*unpublished*).

THULBORN, R.A. (1990) - *Dinosaur Tracks*. Chapman Hall, London, 410 pp.

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A COMPARISON OF WELL-PRESERVED SAUROPOD TRACKS FROM THE LATE JURASSIC OF PORTUGAL AND THE WESTERN UNITED STATES: EVIDENCE AND IMPLICATIONS[1]

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ABSTRACT: We report here on tracksites from Utah and Portugal that reveal what we believe to be the best-preserved, Late Jurassic sauropod ichnites (cf. *Brontopodus*) currently known. The Utah tracks, from Morrison Formation fluvial deposits at the Lost Springs site, are also the first known example of a sauropod trackway segment, from this epoch, preserved as natural casts. Currently there are only three known examples of sites that have yielded sauropod tracks preserved as casts. Based on this small sample, we infer that such a mode of preservation is likely to occur in fluvial depositional environments, but is unlikely to occur in carbonate platform sequences from which the majority of well-preserved sauropod trackways have been reported.

RESUMO: Neste artigo apresentamos as pegadas de saurópodes (cf. *Brontopodus*) do Jurássico superior melhor conservadas, até hoje, encontradas em jazidas do Utah (EUA) e de Portugal. Os icnitos de Lost Springs - Utah, preservados em sedimentos fluviais da Formação Morrison, são também o primeiro exemplo de moldes naturais de pegadas do Jurássico superior, pertencentes a um segmento de pista de saurópode. Até ao momento conhecem-se apenas três jazidas que forneceram icnitos de saurópodes preservados como moldes. Com base nesta pequena amostra inferimos que tal forma de preservação tende a ocorrer em ambientes fluviais em vez de ambientes de sedimentação carbonatada, onde a maioria das impressões de saurópodes bem conservadas têm sido referenciadas.

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INTRODUCTION

The purpose of this paper is to describe what we believe to be the best-preserved Late Jurassic sauropod tracks currently known and to compare them with existing sauropod ichnites. Although the recent renaissance in vertebrate ichnology has resulted in the discovery and documentation of many new sauropod tracksites in different parts of the world, most of the tracks have not been studied in detail. Thus the relationship of these track types to a few well-defined sauropod ichnites such as *Brontopodus birdi* (FARLOW, PITTMAN & HAWTHORNE, 1989) is poorly documented. We herein report that recently discovered Late Jurassic sauropod tracks from Utah and Portugal are quite similar to *B. birdi*, and should therefore be referred to the ichnogenus *Brontopodus*.

THE LOST SPRINGS SITE, GARFIELD COUNTY, EASTERN UTAH

The Lost Springs site was recently discovered by one of us (J.W.R.) during the course of a study of the Salt Wash Member of the Morrison Formation, in the Bullfrog area of eastern Utah. The tracks are preserved as two large natural casts on the underside of a large, buff coloured channel sandstone sitting on fine grained red siltstones. The tracks represent two consecutive right footprints that were made in the fine sediment, then later filled with sand (Fig. 1). The tracks measure 76 cm long by 49 cm wide (first in sequence) and 68 cm by 49 cm (second), and indicate an animal moving towards the southeast (see Fig. 1). Using the measured stride length of 164 cm and the formula of ALEXANDER (1976) a speed of 0.51 $m.s^{-1}$ is estimated (= 1.86 $km.h^{-1}$). The tracks are about 10-15 cm deep and show well developed digit impressions. The impressions of digits I-III indicate the presence of elongate claws, whereas the impressions of digits IV and V indicate the presence of pads or callosities. In this respect the tracks are similar to *Brontopodus birdi* described by FARLOW, PITTMAN & HAWTHORNE (1989), except that the digit IV impression is apparently more pad-like than claw-like in the Utah example. The left footprint that belongs with this short trackway segment is not exposed, so we were unable to determine its correct position in the trackway, and so can not measure either the pace angulation or the trackway width. It is therefore not known whether the animal had a "wide gauge" trackway (*sensu* FARLOW, 1992 and LOCKLEY, FARLOW & MEYER, 1994) similar to *Brontopodus birdi* or a narrow gauge trackway similar to those reported from the Morrison Formation in Colorado (LOCKLEY, HOUCK & PRINCE, 1986) and from the Late Jurassic Avelino site in Portugal (LOCKLEY & SANTOS, 1993). If excavation were to prove this to be a narrow gauge trackway, it could be referred to *Parabrontopodus* (*sensu* LOCKLEY, FARLOW & MEYER, 1994). Manus

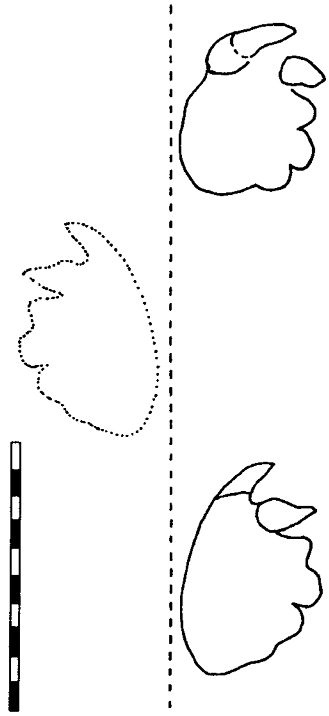

Fig. 1 - **A** - Outline of partial *Brontopodus* trackway from the Lost Springs site, Late Jurassic Morrison Formation, Eastern Utah. Note that the position of the left pes tracks is inferred, and that the edge of the outcrop pases very close to the anterior of the right pes casts, possibly accounting for the lack of manus impressions.

tracks associated with this trackway are not preserved on this small exposure. The reasons for this are not known, but it may simply be that the pes overprinted the manus, or that the manus tracks eroded away because they were situated too close to the weathered edge of the outcrop.

Although the Morrison Formation is known for having yielded sauropod tracks from two large sites in Colorado (LOCKLEY, HOUCK & PRINCE, 1986; LOCKLEY & HUNT, *in press*) few sites have been reported from Utah. This is only the third report of sauropod tracks from Utah (see LOCKLEY, 1991, and LOCKLEY *et. al.*, 1992 for first two reports). Due to the fine detail of the morphology of the pes tracks at the Lost Springs site, and the fact that they are the only natural casts of a Late Jurassic sauropod trackway segment reported to date, the site is very important as a unique record of Late Jurassic brontosaur foot morphology.

To the best of our knowledge, there are only three reports of sauropod tracks preserved as casts. The first, reported by LOCKLEY *et al.* (1992) was of an isolated footprint cast with skin impressions from a horizon in the uppermost part of the Tidwell Member of the Summerville Formation at a locality near Bullfrog. The track was first reported as a probable manus

Fig. 1 (continued) - **B** - Worm's eye view of first track in sequence.

track cast, but has since been reinterpreted as a probable small pes track cast (LOCKLEY & HUNT, *in press*).

The second report of possible sauropod tracks, preserved as casts, comes from the Middle Jurassic of Yorkshire, England (WHYTE & ROMANO, 1993, 1994). These authors described a trackway segment consisting of at least three consecutive manus-pes sets, preserved as natural casts on the underside of thick sandstone beds that overly thin red, sideritic siltstone. Clearly the tracks were made in a fine grained silt and filled in by sand. Currently we are not absolutely certain that the Yorkshire tracks are attributable to sauropods - an uncertainty also shared by FARLOW (*written commun.*, 1994). If further works should prove these tracks to be non-sauropod in affinity, then this would leave the two examples of sauropod track casts from Utah as the only two currently known [see note added in proof].

The tracks from the Lost Springs site are evidently the third example of a partial sauropod trackway preserved as natural casts or in convex hyporelief. It should be noted that tracks preserved as casts were, in most cases, initially made in finer sediment than the infilling, overlying layer. In such fine substrates there is a good potential for the preservation of fine detail such as skin impressions and details of digit and claw morphology.

Two additional examples of possible sauropod tracks, preserved as casts in the Morrison Formation, may be seen on the underside of beds at Dinosaur Ridge, Colorado (LOCKLEY, 1990) and on the underside of lacustrine limestones at the Purgatoire site in Colorado (M.G.L., C.A.M. and V.F.S., *pers. obs.*). However in both these cases the quality of preservation is very poor and the tracks are preserved only as large bulbous bulges, that can hardly be considered diagnostic on the basis of shape. Only their large size, and the known occurrence of many sauropods in this epoch, suggests a probable sauropod affinity for these ichnites.

Since the time of writing this paper, one of us (M.G.L.) has observed sauropod track casts, discovered by John Bird, in the Morrison Formation near the Cleveland Lloyd quarry in Utah [see note added in proof].

THE CABO ESPICHEL SITE, SESIMBRA REGION, PORTUGAL

Fossil footprints have been known from Lagosteiros Bay, near Cabo Espichel in Portugal since the thir-

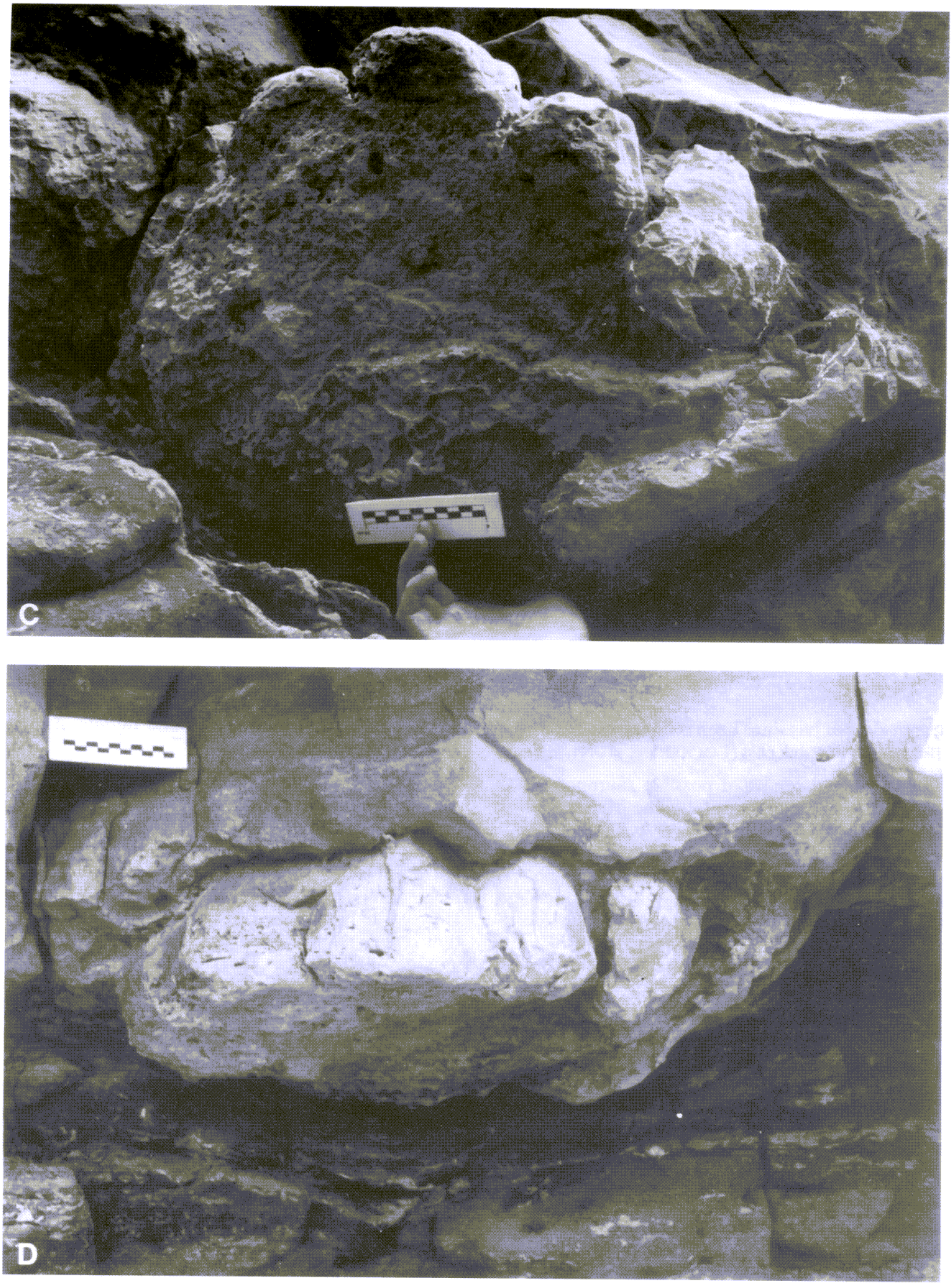

Fig. 1 (continued) - **C** and **D**, worm's eye view and right lateral view of second track in sequence.

teenth century, but, according to local legend, the most prominent trackways were misinterpreted as the trackway of a giant mule (Pegadas de Mula: ANTUNES, 1976; SANTOS, 1990; SANTOS *et al.*, 1992 and LOCKLEY, MEYER & SANTOS, 1994). In recent years however, these trackways, from Portlandian carbonates, were correctly attributed to sauropods (ANTUNES, 1976), though they were not described in detail. We are currently undertaking a study of tracks in this region, and have mapped several track-bearing surfaces, to reveal abundant sauropod trackways (LOCKLEY, MEYER & SANTOS, 1994). On the aforementioned, best-known, track-bearing surface, illustrated by ANTUNES (1976), and now designated as track-level number 5, we have mapped four trackways of medium to large sized sauropods (Fig. 2). Three of these trackways reveal distinctive pes digit impressions, and a representative manus pes set, from the largest trackway, has been replicated (Fig. 3). It is clear from our preliminary study of the trackways that

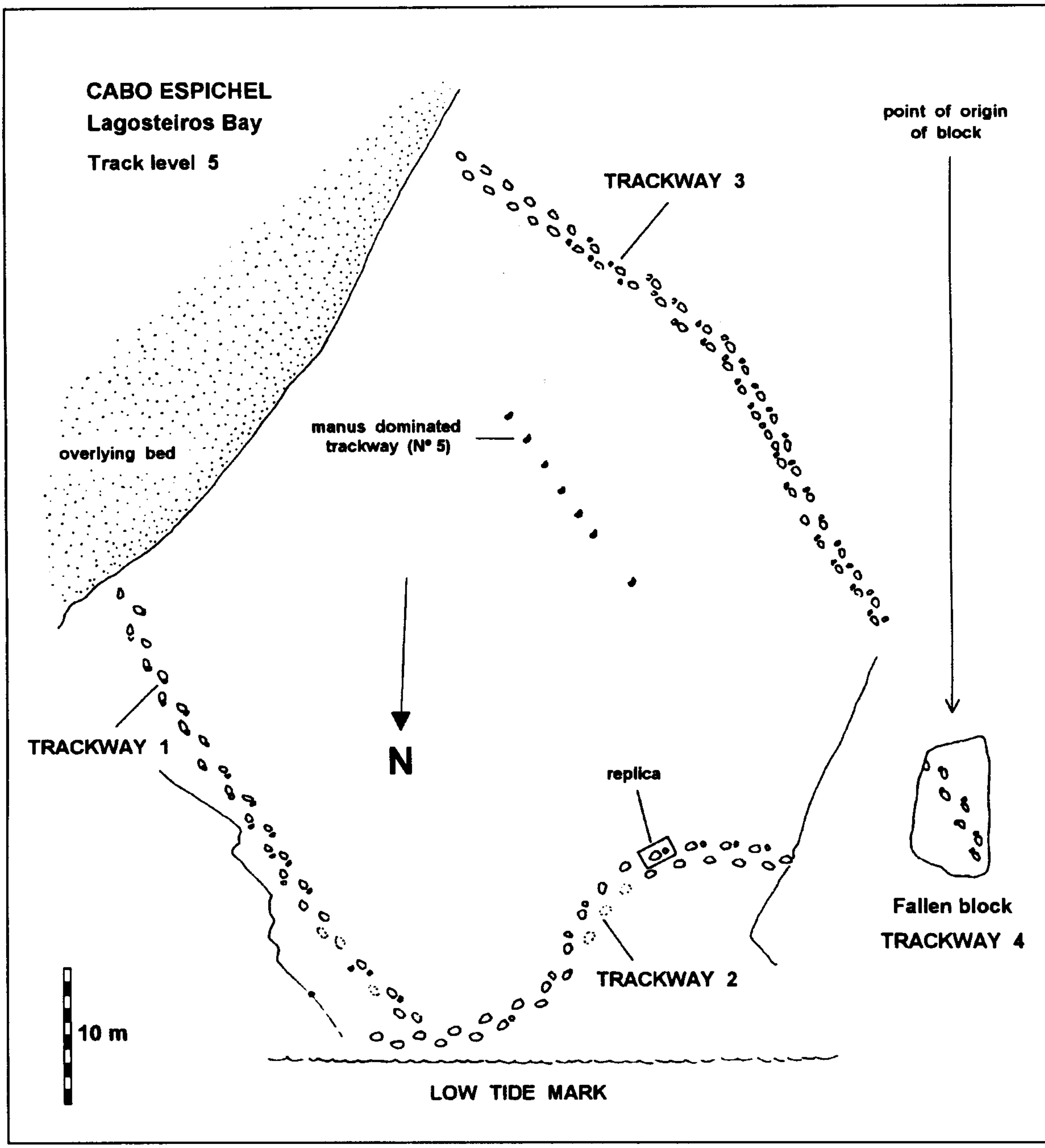

Fig. 2 - Map of track-bearing level number 5, in Portlandian carbonates, Lagosteiros Bay, near Cabo Espichel, Sesimbra Region, Portugal. Trackways 1-3 all show pes digit impressions. Replica shown in Figure 3 is from trackway number 2. Trackway number 3 indicates a limping animal (see DANTAS *et al.*, 1994).

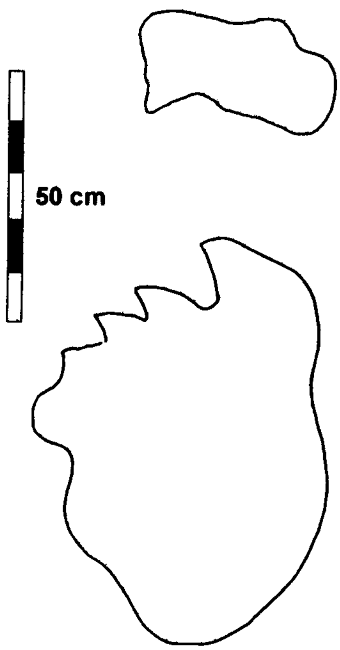

Fig. 3 - Detail of large sauropod manus and pes set (left side) from trackway number 3, track-bearing level number 5, Lagosteiros Bay, near Cabo Espichel, Sesimbra Region, Portugal (specimen number PM-N5 P2 L11).

they are very similar to *Brontopodus*, and we have already designated this track-rich sequence of beds as an example of the *Brontopodus* ichnofacies (LOCKLEY *et al.*, 1994; LOCKLEY, MEYER & SANTOS, 1994). We note that these trackways are moderately wide gauge, *i.e.*, a little narrower than those of *Brontopodus birdi* from Texas (FARLOW, PITTMAN & HAWTHORNE, 1989) but wider than those from the Purgatoire site in southeastern Colorado (LOCKLEY, HOUCK & PRINCE, 1986), see Figure 4.

DISCUSSION AND CONCLUSIONS

When viewed from a global perspective, there have been very few reports of well-preserved sauropod trackways from the Late Jurassic. Most are simply rounded or oval impressions without diagnostic digit impressions. Indeed, with the exception of *B. birdi* from the Cretaceous of Texas, illustrations of sauropod tracks with pes digit impressions, from any epoch, were, prior to the present report, limited to a handful of sparsely documented examples. These are as follows: *Breviparopus taghbaloutensis* from the Middle Jurassic of Morocco, as illustrated by ISHIGAKI (1989), but not in the original description (DUTUIT & OUAZZOU, 1980), a possible example of an unnamed ichnite from the Middle Jurassic of England (WHYTE & ROMANO, 1993), a previously unamed ichnite from the Late Jurassic of Colorado (LOCK-

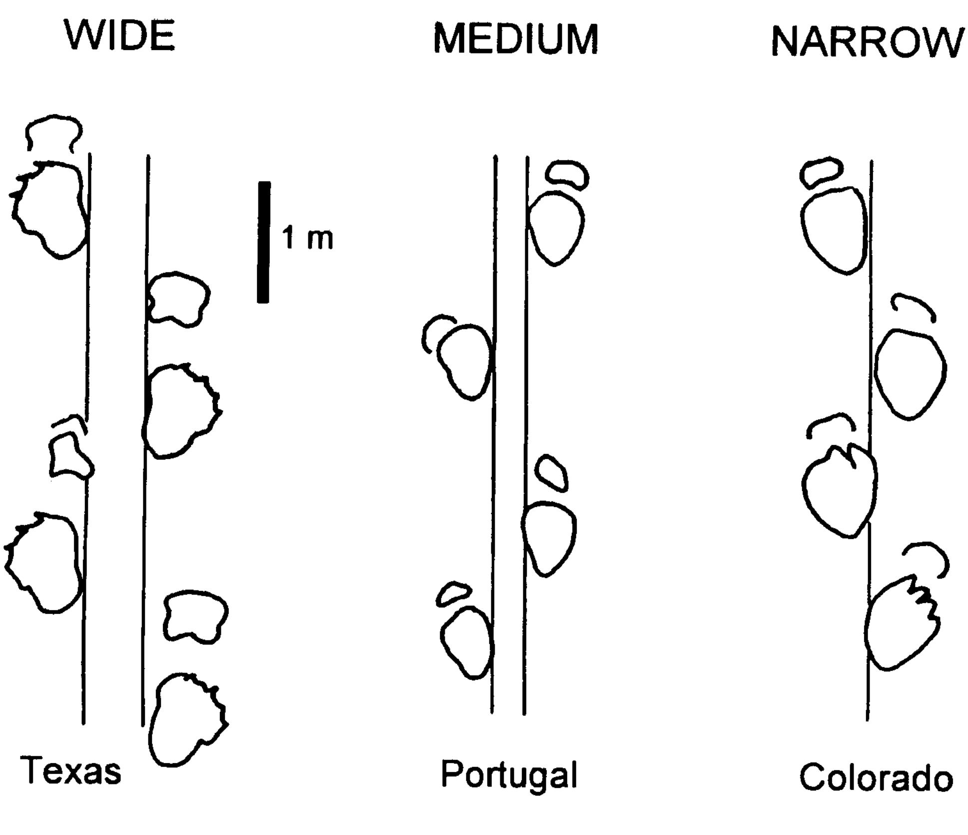

Fig. 4 - Wide-, medium- and narrow-gauge sauropod trackways respectively from the Cretaceous of Texas and the Upper Jurassic of Portugal and Colorado (modified after FARLOW, 1992 and LOCKLEY & HUNT, *in press*).

LEY, HOUCK & PRINCE, 1986), now named *Parabrontopodus mcintoshi* (LOCKLEY, FARLOW & MEYER, 1994), and an unamed ichnite from the ?Late Jurassic to Early Cretaceous of North Africa (GINSBURG *et al.*, 1966). There are also very few valid names for sauropod ichnites from the Late Jurassic, or from any other epoch (LOCKLEY, FARLOW & MEYER, 1994). As discussed elsewhere in this volume, we recognize only the following as valid ichnospecies *Brontopodus birdi* (FARLOW, PITTMAN & HAWTHORNE, 1989), a wide gauge trackway (*sensu* FARLOW, 1992; LOCKLEY, FARLOW & MEYER, 1994), *Breviparopus taghbaloutensis*, a narrow gauge trackway (DUTUIT & OUAZZOU, 1980), *Parabrontopodus mcintoshi*, another narrow gauge trackway (LOCKLEY, FARLOW & MEYER, 1994), and possibly *Rotundichnus münchehagensis*, a wide gauge trackway (HENDRICKS, 1981), as valid ichnospecies.

The only large sample of reasonably well-preserved late Jurassic sauropod trackways, with pes claw impressions, documented prior to the present study was that reported from the Late Jurassic Morrison Formation of Colorado (see LOCKLEY, HOUCK & PRINCE, 1986 and this volume). These include shallow examples of a large morphotype with impressions of pes digits (see Fig. 4). Therefore, the discovery of the Lost Springs, and Lagosteiros Bay ichnites is a significant addition to our knowledge of sauropod ichnites from this epoch.

Although the Late Jurassic Epoch is traditionally regarded as the "Age of Brontosaurs", and trackways attributable to sauropods are known, there have been surprisingly few reports of well-preserved trackways. Until recently, by far the best-preserved sauropod ichnites from this epoch were the unnamed examples from the Morrison Formation in Colorado (LOCKLEY, HOUCK & PRINCE, 1986), and the poorly dated and poorly documented North African examples from ?Late Jurassic - ?Early Cretaceous deposits. The new track discoveries reported herein, add significantly to our data base of well-preserved Late Jurassic sauropod ichnites, by providing two of the three best examples currently known (the third being the trackways from the Purgatoire site in Colorado, LOCKLEY, HOUCK & PRINCE, 1986). Preliminary results suggest that general pes morphology is similar to *Brontopodus* from the Cretaceous of Texas. However, in the case of the Lost Springs ichnites, the pads associated with the outer digit impressions, appear, blunter and a little less claw like than in *Brontopodus*. This observation suggests that the Lost Springs tracks may be differentiated from *B. birdi* at the level of ichno-species. This is not surprising, since it is virtually certain that the Late Jurassic trackmaker was not the same species as the Cretaceous trackmaker from Texas.

We also note that the Lost Springs ichnites owe their exceptional preservation to the fact that they are preserved as natural casts, and were originally made in fine-grained muddy sediments. Such a mode of preservation is not uncommon for large Cretaceous ornithopod tracks found in alternating fine and coarse grained lithologies, for example in coal-bearing, coastal plain deposits (LOCKLEY, YOUNG & CARPENTER, 1983; LOCKLEY *et al.*, 1992; PARKER & BALSLEY, 1989), but, until now has proved a little-known mode of preservation for sauropod ichnites. This is in part due to the fact that most sauropod tracks occur in carbonate platform sequences that lack the right type of alternating lithologies, but also due to the simple fact that exposures of the underside of bedded units, where casts are found, are much less extensive than exposures of the upper surfaces.

Five of the six known examples of sauropod track casts, three from Utah (LOCKLEY *et al.*, 1992 and this paper), one from Colorado (LOCKLEY, 1990), and one from England (WHYTE & ROMANO, 1993) are associated with fluvial deposits where massive sandstones alternate with fine-grained floodplain deposits. This style of preservation, is evidently related to depositional regime, as might be expected.

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NOTE ADDED IN PROOF

Recent preliminary investigations of new sauropod tracksites in the Saltwash and underlying Summerville Formation of Utah and Arizona respectively have revealed additional examples of sauropod pes casts. One particularly well preserved example in illustrated in LOCKLEY, FARLOW & MEYER (1994).

REFERENCES

ALEXANDER, R.M. (1976) - Estimates of speeds of dinosaurs. *Nature*, **261:** 129-130.

ANTUNES, M.T. (1976) - Dinossáurios Eocretácicos de Lagosteiros. *Ciências da Terra*, **1**, 35 pp.

DANTAS, P.; SANTOS, V.F.; LOCKLEY, M.G. & MEYER, C.A. (1994) - Footprint evidence for limping dinosaurs from the Upper Jurassic of Portugal. *Gaia* (*this volume*).

DUTUIT, J.-M. & OUAZZOU, A. (1980) - Découverte d'une piste de dinosaure sauropode sur le site d'empreintes de Demnat (Haut-Atlas Marocain). *Mém. Soc. Géol. France*, N. S., **139**: 95-102.

FARLOW, J.O. (1992) - Sauropod Tracks and trackmakers: integrating the ichnological and skeletal records. *Zubia*, **10**: 89-138.

FARLOW, J.O.; PITTMAN, J.G. & HAWTHORNE, J.M. (1989) - *Brontopodus birdi*, Lower Cretaceous sauropod footprints from the U.S. Gulf coastal plain *in* GILLETTE, D.D. & LOCKLEY, M.G. (Eds), *Dinosaur Tracks and Traces*, Cambridge Univ. Press, Cambridge, pp. 371-394.

GINSBURG, L.; LAPPARENT, A.F.DE; LOIRET, B. & TAQUET, P. (1966) - Empreintes de pas de Vertébrés tétrapodes dans les Séries continentales à l'Ouest d'Agadés (République du Niger). *C. R. Acad. Sci., Paris*, **263**: 28-31.

HENDRICKS, A. (1981) - Die Saurierfährten von Münchenhagen bei Rehburg-Locum (NW-Deutschland). *Abhandl. Landesmuseum Naturkunde Münster Westfalen*, **43**(2): 1-22.

ISHIGAKI, S. (1989) - Footprints of swimming sauropods from Morocco *in* GILLETTE, D.D. & LOCKLEY, M.G. (Eds), *Dinosaur Tracks and Traces*, Cambridge Univ. Press, Cambridge, pp. 83-86.

LOCKLEY, M.G. (1990) - *A Field Guide to Dinosaur Ridge*. Friends of Dinosaur Ridge - Univ. Colorado, Denver, joint publication, 32 pp.

LOCKLEY, M.G. (1991) - *Tracking Dinosaurs: a new look at an ancient world*. Cambridge Univ. Press, Cambridge, 238 pp.

LOCKLEY, M.G.; FARLOW, J.O. & MEYER, C.A. (1994) - *Brontopodus* and *Parabrontopodus* ichnogen nov. and the significance of wide and narrow gauge sauropod. *Gaia (this volume)*.

LOCKLEY, M.G.; HOUCK, K.J. & PRINCE, N.K. (1986) - North America's largest dinosaur trackway site: implications for Morrison paleoecology. *Bull. Geol. Soc. Am.*, **97**: 1163-1176.

LOCKLEY, M.G. & HUNT, A.P. (*in press*) - *Dinosaur Tracks and other fossil footprints from the western United States*. Columbia Univ. Press.

LOCKLEY, M.G.; HUNT, A.; CONRAD, K. & ROBINSON, J. (1992) - Tracking dinosaurs and other extinct animals at Lake Powell. *Park Sci.: A Resource Management Bull.*, **12**: 16-17.

LOCKLEY, M.G.; HUNT, A.P. & MEYER, C.A. (1994) - Vertebrate tracks and the Ichnofacies Concept: implications for paleoecology and palichnostratigraphy *in* DONOVAN, S. (Ed.), *The Paleobiology of Trace Fossils*, Wiley & Sons, New York, pp. 241-268.

LOCKLEY, M.G.; MEYER, C.A. & SANTOS, V.F. (1994) - Trackway evidence for a herd of juvenile sauropods from the Late Jurassic of Portugal. *Gaia (this volume)*.

LOCKLEY, M.G. & SANTOS, V.F. (1993) - A preliminary report on sauropod trackways from the Avelino Site, Sesimbra Region, Upper Jurassic, Portugal. *Gaia*, **6**: 38-42.

LOCKLEY, M.G.; YOUNG, B.H. & CARPENTER, K. (1983) - Hadrosaur locomotion and herding behavior: evidence from footprints from the Mesa Verde Formation, Grand Mesa Coalfield, Colorado. *The Montain Geologist*, **20**: 5-14.

PARKER, L. & BALSLEY, J. (1989) - Coal mines as localities for studying dinosaur trace fossils *in* GILLETTE, D.D. & LOCKLEY, M.G. (Eds), *Dinosaur Tracks and Traces*, Cambridge Univ. Press, Cambridge, pp. 353-359.

SANTOS, V.F. (1990) - Icnofósseis de dinossáurios de Portugal. Alguns aspectos paleoecológicos. *Seminário Científico, Fac. Ciências, Univ. Lisboa*, 36 pp. *(unpublished)*.

SANTOS, V.F.; LOCKLEY, M.G.; MORATALLA, J.J. & GALOPIM DE CARVALHO, A.M. (1992) - The longest dinosaur trackway in the world? Interpretations of Cretaceous footprints from Carenque, near Lisbon, Portugal. *Gaia*, **5**: 18-27.

WHYTE, M.A. & ROMANO, M. (1993) - Footprints of a sauropod from the Middle Jurassic of Yorkshire. *Proc. Geologists Assoc.*, **104**: 195-199.

WHYTE, M.A. & ROMANO, M. (1994) - Probable sauropod footprints from the Middle Jurassic of Yorkshire, England. *Gaia (this volume)*.

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Trypanites ichnofacies: Palaeoenvironmental and tectonic implications. A case study from the Miocene disconformity at Foz da Fonte (Lower Tagus Basin, Portugal)

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ABSTRACT

A well preserved bioeroded surface occurs at the unconformity separating Cretaceous limestones and Lower Miocene sediments, outcropping on the western coast of the Peninsula of Setúbal (Central West Portugal). The ichnoassemblage present in this bioeroded surface is herein assigned to the *Trypanites* ichnofacies. The preservation characteristics of the borings reflect several episodes of encrustation/boring and physical erosion. The erosional truncation of bioerosive structures, and the predominant preservation of the largest borings (*Gastrochaenolites* isp.) in the ichnocoenoses are herein related with repeated phases of bioerosion and physical abrasion occurred during an Early Miocene transgressive pulse. The recognition of this bioeroded transgressive surface also allowed confirming the presence, at that time, of an emergent topographic relief related to salt domes formed earlier, probably already during Palaeogene times.

1. Introduction

Preservation of rocky palaeoshore indicators along modern coastlines is limited and commonly confined to favourable localities. As a rule, these environments are susceptible to tectonic uplift and erosion degradation over short periods of geological time (Johnson et al., 1998). However, the wealth of publications about this particular subject clearly demonstrates that fossil rocky shores are more common than previously believed and can occur in a wide range of rock types and ages (Radwanski, 1970; Palmer, 1982; Brett and Brookfield, 1984; Wilson, 1985, 1987; Johnson and Baarli, 1987; Johnson, 1988a,b; Pirazzoli et al., 1994; Brett, 1998; Bertling, 1999; Johnson and Baarli, 1999; Ekdale and Bromley, 2001; Benner et al., 2004; Plag, 2006; Johnson, 2006; Santos et al., 2008; Cachão et al., 2009).

A hardground is a stratigraphic discontinuity in carbonate seafloors where lithification has taken place before the development of a permanent sedimentary cover (synsedimentary lithification) (Voigt, 1959; Goldring and Kaźmierczak, 1974; Bromley, 1975). These conditions may occur near the end of a transgressive cycle in a carbonate sequence, producing a hardground as the maximum flooding surface (Taylor and Wilson, 2003). Thus, hiatus beds have stratigraphic and sedimentologic value in that they allow identification of surfaces at which sedimentation was interrupted for a significant time (Wilson, 1985; Wilson and Palmer, 1992; Taylor and Wilson, 2003; Santos et al., 2008), and also can be related to sea level changes (e.g., Kendal and Schlager, 1981; Fürsich et al., 1991; Ghibaudo et al., 1996; Cachão et al., 2009).

Euendoliths, which deeply penetrate lithified substrates, correspond to benthic organisms that produce permanent dwelling structures (domichnia) in hard substrates (Ekdale and Bromley, 2001), and usually significantly bioerode the host rock. The exhumation of cemented substrates provides extensive surfaces for infestation by benthic epilithic and euendolithic organisms. This may result in the development of hard lithified substrate ichnocenoses assigned to the *Trypanites* ichnofacies.

The study of the distribution and preservation mode of these trace fossils provide invaluable data for the understanding of hard substrate biota. The presence and the activity of the different benthic organisms that inhabited the substrate are recorded as a composite ichnofabric (Ekdale et al., 1984; Bromley and Ekdale, 1986). According to the range of tolerance of benthic organisms, successive suites of trace fossils appear. Each stage of substrate evolution is marked by organisms able to colonize the substrate under those specific conditions. Therefore, encrustations and/or borings in unconformity surfaces are the best confirmation of the existence of an ancient rocky-shore (Johnson, 2006), and are paramount for reconstruction of the palaeoenvironments

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related to sedimentary discontinuities (Ghibaudo et al., 1996; Cachão et al., 2009).

According to Johnson and Ledesma-Vázquez (1999) rocky palaeoshores and their biota are inherently interesting because they represent the palaeoecological history of a complex ecosystem, and because they have the potential to solve associated geological problems.

In this context, the aims of this study are twofold: (1) to survey the palaeoecological succession of encrusting and bioeroding organisms of the ichnoassemblage exhibited by the fossil rocky-shore biota; and (2) to show the relevance of trace fossil analysis to palaeoecological and tectonic studies, based on the Miocene geological history of the Arrábida Chain (Central West Iberian Peninsula, Portugal).

2. Geologic and tectonic setting

The Foz da Fonte study area (Fig. 1) is localized in the West Iberian Margin (WIM). This margin evolved during the Alpine Cycle and was conditioned by several tectonic events: 1) from Late Triassic to Early Cretaceous several extensional basins were formed, related to the early phases of the North Atlantic opening (Wilson et al., 1989; Rasmussen et al., 1998; Kullberg, 2000); 2) during the Late Cretaceous, after it became a passive margin, alkaline magmatism and salt diapirism were widespread in the whole region, (Kullberg et al., 2006a; Miranda et al., 2009); 3) during the Miocene (Burdigalian–Tortonian) a compressional episode related to the North directed convergence between the Eurasian and African plates took place (Ribeiro et al., 1990; Kullberg et al., 2006b). This superposition of tectonic events was responsible for major unconformities and hiatus in the entire onshore region of the WIM.

Regional geological mapping (e.g. Manuppella (coord.), 1994) clearly shows that the Palaeogene deposits of the Sesimbra–Foz da Fonte area are geometrically and genetically associated with the Cova da Mijona salt dome. In the axis of this structure the Miocene sediments lie directly, slightly unconformable, on the Cretaceous units (Fig. 2). The Foz da Fonte is one of the most relevant and better exposed outcrops where that hiatus is represented.

The bioeroded surface of Foz da Fonte is associated with a low angle unconformity, and it occurs directly imprinted on strongly lithified Cretaceous (Albian) fossiliferous limestones. These limestones also show evidences of emersion and incipient karst development mainly concentrated around fractures produced by a dyke field related to a doloritic sill intruded in the Albian limestones, approximately 10 m below the bioeroded surface. This intrusion was dated by $^{40}Ar/^{39}Ar$ geochronology, resulting in a reverse isochron age of 93.8 ± 3.9 Ma (Miranda et al., 2006, 2009). Evidences of emersion and karstification prior to the transgressive Lower Miocene depositional cycle indicate that in the western sector of the forthcoming Arrábida Chain, some emerged relief structures already existed, prior to the onset of this small tectonic chain. Those reliefs are the Sesimbra and Cova da Mijona salt domes, located to the East and Southeast of the study area, related to Late Cretaceous/Early

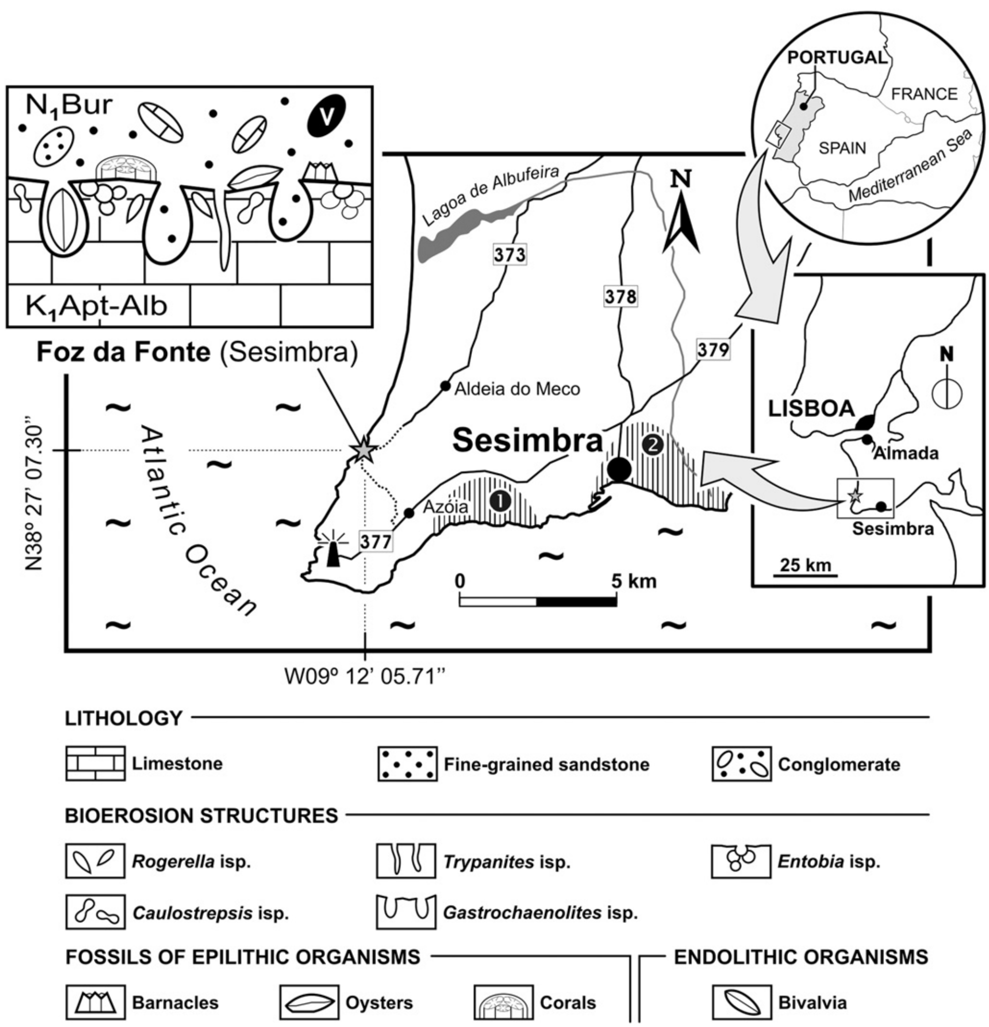


Fig. 1. Geographical and geological setting of Foz da Fonte outcrop (Central West Portugal) featuring bioerosion structures associated with the studied hardground. Dashes are the emerged areas related of: 1 — Cova da Mijona dome; 2 — Sesimbra diapir.

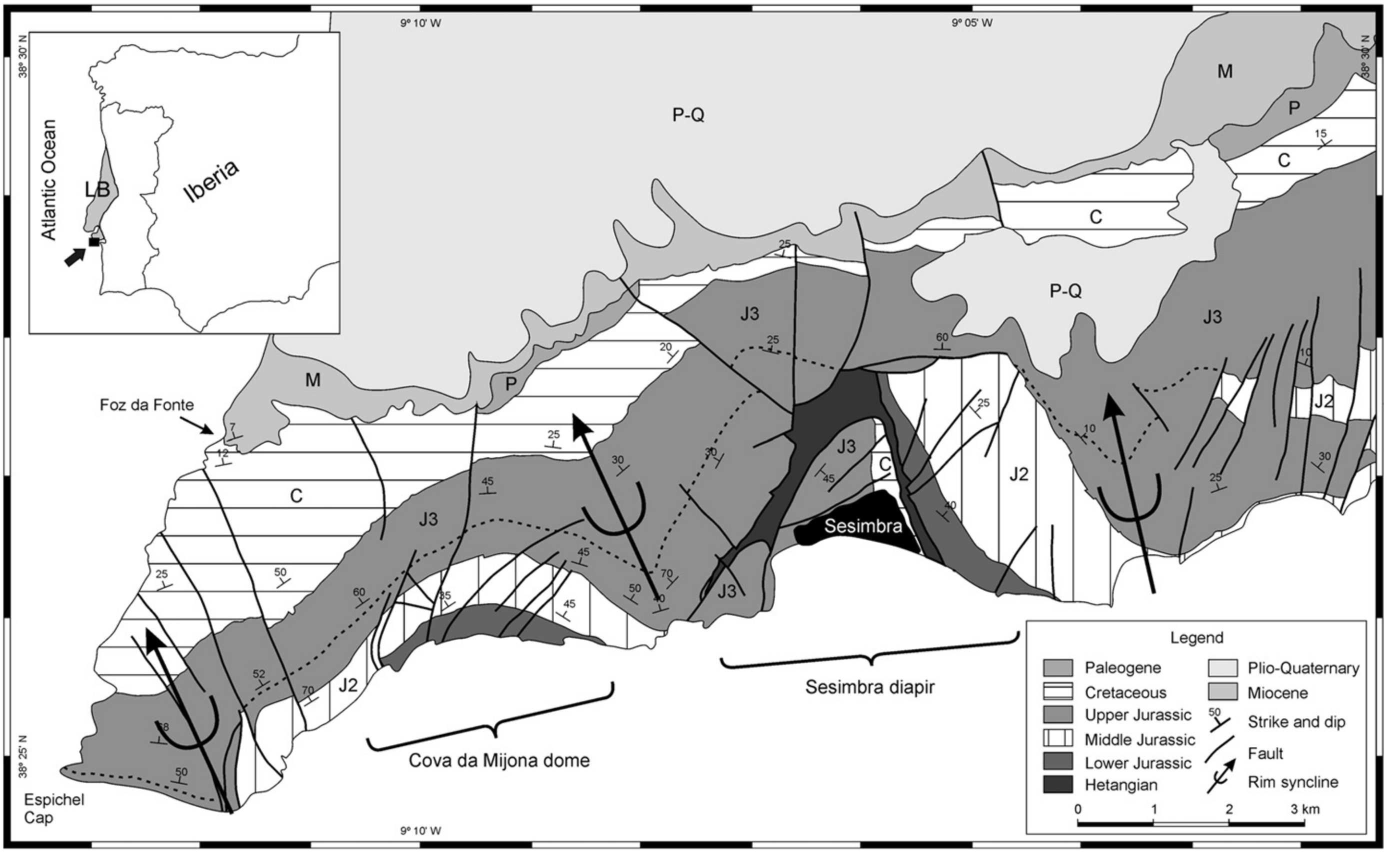


Fig. 2. Geological and tectonic sketch map of the eastern sector of the Arrábida Chain (adapted from Manupella (coord.), 1994), and location of the study area in the West Iberian Margin (inset).

Palaeogene salt diapirism (Kullberg and Rocha, 1991; Kullberg et al., 2000) (Fig. 2).

From a tectonic point of view, the main question here is to assess whether this sector of the Setúbal Peninsula was already uplifted before the Betic deformation phase evidenced at Portinho da Arrábida (Ribeiro et al., 1979), about 25 km East of the Foz da Fonte outcrop. At Portinho da Arrábida, an angular unconformity of about 90° marks a hiatus between 17.5 and 16.5 Ma dated using $^{87}Sr/^{86}Sr$ isotopes (Antunes et al., 1995).

3. The Foz da Fonte Miocene bioeroded surface

The bioeroded surface is located on the Atlantic coast of the Setúbal Peninsula, Central West Portugal, about 30 km southwest of Lisbon (Fig. 1). It corresponds to a sub-horizontal transgressive surface that cuts through a previous emerged and karstified Cretaceous carbonate relief, having a total area of 468 m^2 and a dip of 50°N 8°SE. The surface is positioned about 10 m above the present day mean sea level.

The Foz da Fonte bioeroded surface, as well as the bioerosion structures affecting it, is Miocene in age and developed unconformably on the contact between Lower Cretaceous limestones (Albian age) below, and Lower Miocene clayey and calcarenitic sediments above (Manupella et al., 1999) (Fig. 3).

The surface is extensively bored, showing numerous ichnofossils in 80 to 90% of its surface (Fig. 4). The bioeroded surface also presents evidences of encrusting organisms, such as the pycnodontic bivalve *Pycnodonte squarrosa*, preserved with its original shell, basal plates of balanomorphs, and colonial corals *in situ*. Several bivalves sometimes grew over the borings, indicating a later larval settlement, and others are also perforated by boring bivalves, representing a second colonization and bioerosion phase. Mineral encrustations over the surface and covering on the borings are missing.

Neogene bioerosion structures at Foz da Fonte have been previously reported by Silva et al. (1999), who described this contact surface as a hard Miocene bioeroded surface with abundant bivalve and sponge borings.

4. Methods

To perform this study, seventeen 20×20 cm^2 areas of substrate were randomly selected. The bioerosion structures within these areas were identified and counted, and the remains of encrusting organisms were recorded. After identification, the estimation of the real composition of the ichnocenoses was made. The bioerosion structures were measured using digital callipers. The spatial relationships between bioerosion structures and encrusting organisms were also recorded.

The biostratigraphy of the overlying Miocene beds was determined using calcareous nannofossils. Thirteen sediment replicates were collected in the dark grey fossiliferous clay immediately above the bioerosioned surface. Each replicate sample was prepared following the rippled smear slide procedure described in Cachão and Moita (2000) and the nannofossil assemblages screened for biostratigraphy markers at $\times 1250$ magnification under a petrographic optical microscope.

5. Results

5.1. Palaeoichnology

The morphological analysis of the bioerosion structures preserved revealed seven ichnospecies belonging to five ichnogenera (Table 1). These include structures produced by polychaete annelids (*Caulostrepsis* isp.), clionaid sponges (*Entobia* isp.), sipunculid annelids (*Trypanites weise* Mägdefrau, 1932), acrothoracican cirripedia (*Rogerella* isp.) and endolithic bivalves (*Gastrochaenolites torpedo* Kelly and Bromley, 1984,

Fig. 3. Contact surface between Cretaceous limestones (Albian) and Miocene (Middle-Upper Burdigalian) terrigenous sediments at Foz da Fonte (Portugal). Bioerosion structures occur below the planar surface that bounds both rock units. N_1Bur—Miocene, Burdigalian; K_1Alb—Lower Cretaceous, Albian. Age symbols and stage abbreviations after Harland et al. (1989).

Gastrochaenolites lapidicus Kelly and Bromley, 1984, *Gastrochaenolites ornatus* Kelly and Bromley, 1984). All the bioerosion structures correspond to the boring activity of endolithic organisms and, from an ethological point of view, only dwelling structures (domichnia) are present.

The five ichnogenera: *Caulostrepsis*, *Entobia*, *Rogerella*, *Trypanites* and *Gastrochaenolites*, are characteristic of a hard substrate colonization episode. The most prominent trace fossil found is the characteristic club-shape bivalve boring *Gastrochaenolites* preserved in concave epirelief on the bioeroded surface. Field counts (including all the three *Gastrochaenolites* ichnospecies), point to a potential maximum concentration of 50 bivalve borings per 400 cm^2 in some areas, although presenting a very irregularly clustered distribution.

Most *Gastrochaenolites* perforations on the study surface show partial to nearly complete erosion of the original boring. In very rare cases, the vertical *Gastrochaenolites* borings contain evidences of the trace-producing organisms preserved in living position. Some *Gastrochaenolites* borings are oriented perpendicular to the bedding plane (mainly *Gastrochaenolites lapidicus* and *Gastrochaenolites ornatus*), whilst others are subparallel to it (*Gastrochaenolites torpedo*).

Gastrochaenolites ichnospecies were identified on the basis of the shape of the distal part of the boring: *Gastrochaenolites torpedo* (with an acutely parabolic base), *Gastrochaenolites lapidicus* (with a short,

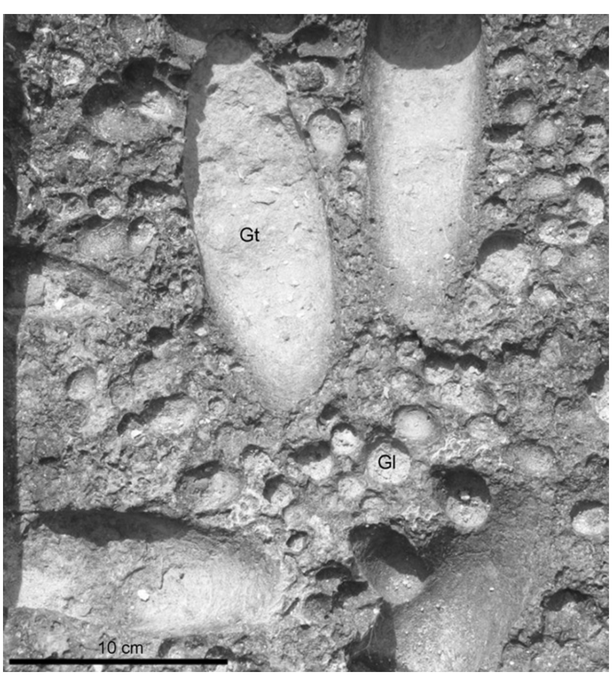


Fig. 4. Detail of the hardground surface with *Gastrochaenolites torpedo* (Gt) and *Gastrochaenolites lapidicus* (Gl).

Table 1
Information of Foz da Fonte bioerosion structures associated with the rocky palaeoshore. Abbreviations and symbols used in the table: * = Age symbols and stage abbreviations after Harland et al. (1989): N1 = (Lower Neogene); Bur = (Burdigalian); K1 = (Lower Cretaceous).

Substrate	Outcrop Portugal Foz da Fonte N_1 Bur
Age (*)	K_1
Lithology	Limestone
Exposure type	Surface
Surface preservation	Regular
Ichnotaxa	
Gastrochaenolites torpedo Kelly and Bromley	●
Gastrochaenolites lapidicus Kelly and Bromley	●
Gastrochaenolites ornatus Kelly and Bromley	●
Entobia isp.	●
Caulostrepsis isp.	●
Trypanites weise Mägdefrau	●
Rogerella isp.	●
Epilithobionts	
Pycnodonte squarrosa	●
Barnacles	●
Colonial corals	●

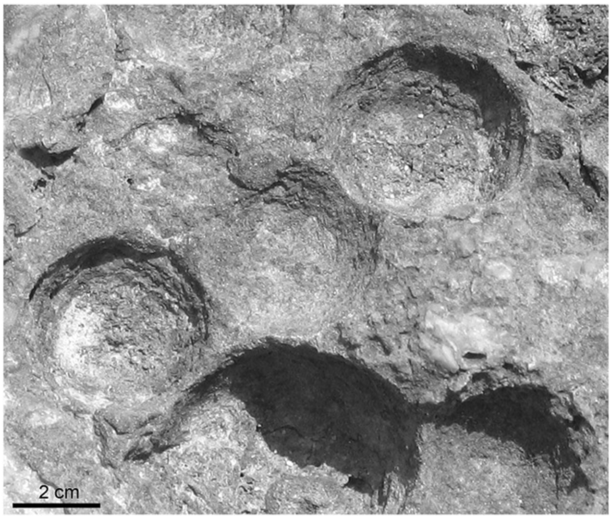


Fig. 5. Plain view of *Gastrochaenolites ornatus* in cross-section, showing the typical bioglyphs on the basal region of the cavity.

rounded base), and *Gastrochaenolites ornatus* (with a short rounded base and bioglyphs on the walls).

At Foz da Fonte, the *Gastrochaenolites torpedo* structures show a mostly wide elongated outline in longitudinal section (subparallel to the bedding plane), and are sparsely distributed on the surface. The tapering in the distal part of the boring is gradual, resulting in a rounded terminal region. The upper half of the borings has been eroded away. The structures vary in dimension: 8.5 cm of maximum length and 3.4 cm of maximum width. The total number of *G. torpedo* structures considered was 102.

Gastrochaenolites lapidicus is much more abundant and evenly distributed on the surface, and mostly oriented perpendicular to the bedding surface. The structures are represented by the lower part of the clavate-shaped boring, showing a circular outline with a rounded base in plain view. The diameter of the borings varies from 0.5 to 1.3 cm, with an average value of 0.7 cm. The total number of *G. lapidicus* structures considered was 435.

Gastrochaenolites ornatus structures are the less common of all, being similar in dimensions to *Gastrochaenolites lapidicus*. These borings typically show concentric sculpturing in the walls (bioglyphs) on the basal region of the cavity (Fig. 5). The area between bivalve borings is occupied by sponge borings *Entobia* Bronn (1837–1838), which have been eroded in most areas, exposing chambers and canals.

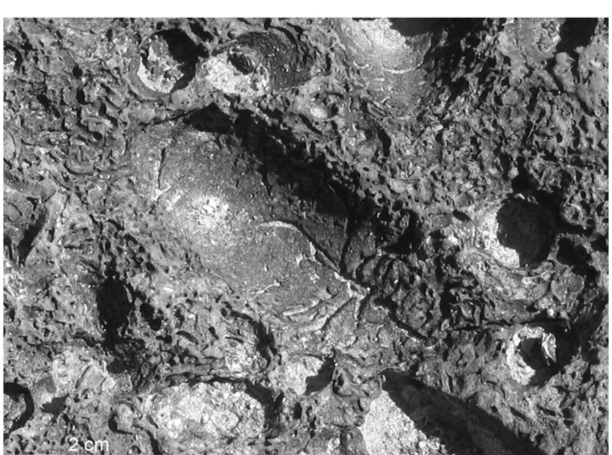


Fig. 6. *Trypanites weise* inside of *Gastrochaenolites torpedo* borings.

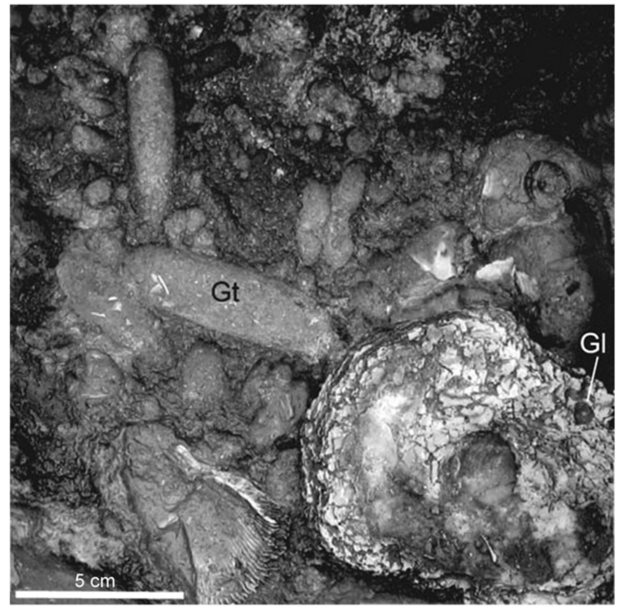


Fig. 7. Left valve of *Pycnodonte squarrosa* with *Entobia*, *Caulostrepsis* and *Gastrochaenolites* bioerosion on the inner surface. Gt—*Gastrochaenolites torpedo* borings; Gl—*Gastrochaenolites lapidicus* borings.

Narrow vertical borings as *Trypanites weise* were identified inside of *Gastrochaenolites torpedo* or perpendicular to the bedding (Fig. 6), with 1 mm diameter and reaching over 12 cm in length.

Caulostrepsis worm borings (with the typical constricted section on figure-of-eight) and acrothoracican cirriped borings *Rogerella* (with their slit-like apertures), were also identified. These two types of trace fossils have a restricted distribution on the surface occurring mainly on the external part (seaward, presently) of the platform.

The encrusting epifauna on the hardground included several organisms like the bivalve *Pycnodonte squarrosa* (de Serres, 1843), barnacles, and colonial corals, all represented by *in situ* remains (Table 1; Figs. 7 and 8). The existence of this community of sclerobionts is further evidence of the existence of a lithified substrate. The encrusting bivalve shells commonly exhibit *Entobia*, *Caulostrepsis*, and *Gastrochaenolites*

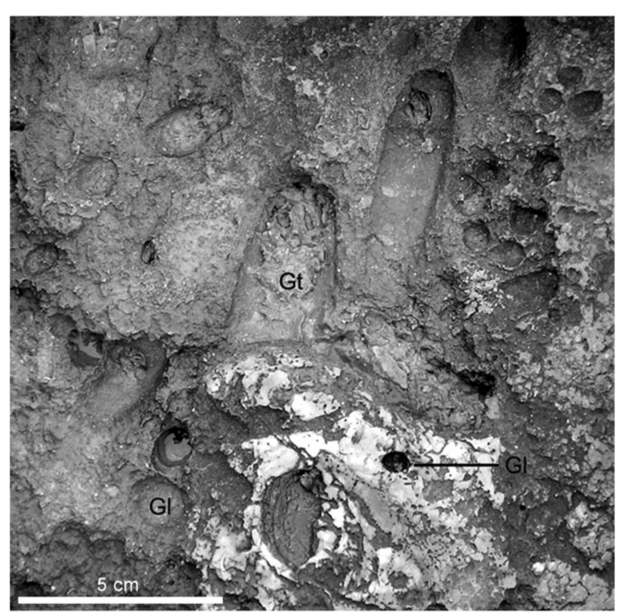


Fig. 8. Spatial distribution of *Gastrochaenolites lapidicus* and *Gastrochaenolites torpedo* structures showing phobotaxis behaviour. Note bivalve shell bored by *G. lapidicus* and encrusting previous *G. torpedo* structures.

borings (Fig. 7). The shells sometimes overgrew previous borings, indicating a later larval settlement. In some of the shells, *Caulostrepsis* structures show evidences of having been produced during the life time of the host, as they exhibit a preferred location and outwards orientation on the outer ventral edge of the shells. Similar boring orientations have been observed and discussed by Santos and Mayoral (2007). The inner surface of disarticulated *Pycnodonte* left valves was mainly colonized by *Entobia*-producing organisms, always from the outside to the inner part of the shell, and barnacles.

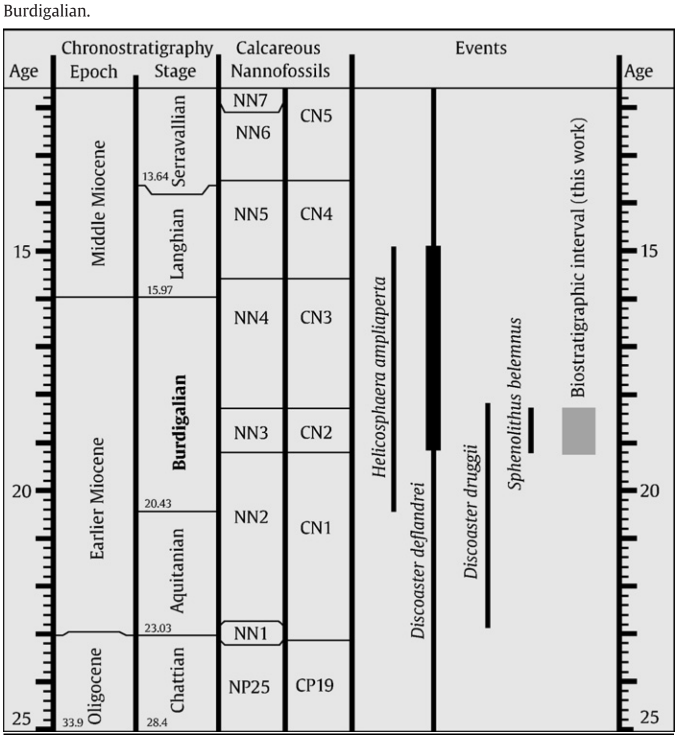
5.2. Calcareous nannofossil biostratigraphy

The calcareous nannofossil assemblages examined are dominated by small forms with less than 3.5 µm, namely *Reticulofenestra minuta* Roth and *Dictyococcites productus* (Kamptner) Backmann. The remaining assemblage is relatively diversified and composed by *Braarudosphaera bigelowii* (Gran and Braarud) Deflandre, *Cyclicargolithus floridanus* (Roth and Hay) Bukry, *Coccolithus pelagicus* (Wallich) Schiller, *C. miopelagicus* Bukry, *Discoaster deflandrei* Bramlette and Riedel, *Discoaster* cf. *druggii* Bramlette and Wilcoxon, *Helicosphaera ampliaperta* Bramlette and Wilcoxon, *H. carteri* (Wallich) Kamptner, *H. carteri wallichii* (Lohmann) Boudreaux and Hay, *H. intermedia* Martini, *H. mediterranea* Müller, *H. vedderi* Bukry, *Holodiscolithus macroporus* (Deflandre) Roth (holococcolith), *Pontosphaera multipora* (Kamptner) Roth, *Reticulofenestra* gr. *haqii* Backman — *minutula* Haq and Berggren; *Sphenolithus belemnos* Bramlette and Wilcoxon, *S. moriformis* Bramlette and Wilcoxon, *Syracosphaera* sp., *Umbilicosphaera jaffari* Müller, and *U. rotula* (Kamptner) Backman, together with ascidian spicules (e.g. *Micrascidites vulgaris* Deflandre and Deflandre–Rigaud).

From a biostratigraphic point of view, the occurrence of *Sphenolithus belemnos* restricts this assemblage to the biozone NN3 (Martini)–CN2 (Okada and Bukry), a short biozonal interval chronostratigraphically equivalent to the Middle Burdigalian (Table 2). For complementary taxonomic and biostratigraphic references see Bown (1998) and Perch-Nielsen (1989).

It is interesting to note that this result matches perfectly with the pioneer stratigraphic conclusion of Berkeley Cotter (Choffat, 1950), more than a century ago, based on mollusc fossil assemblages. Nevertheless other authors indicate older ages for this Miocene beds, such as Aquitanian (Manuppella et al., 1999) or Lower Burdigalian (Antunes et al., 2000).

Table 2
Biostratigraphic table with calcareous nannofossils biozones and the main markers found in the Foz da Fonte lower dark clay unit, immediately above the bioerosioned surface. In grey is the biostratigraphic interval for the assemblage, equivalent to the NN3 (Martini)—CN2 (Okada and Bukry) biozones, and chronostratigraphically equivalent to the Middle Burdigalian.



6. Discussion

6.1. Succession of the bioeroder community

The ichnoassemblage under consideration exhibits post-omission suites recognized by Bromley (1975) as borings that were drilled after lithification. The dense population of *Gastrochaenolites* records a period of non-deposition and exposure of the hardground surface to marine waters. According to Bromley (1992) and Bromley and Asgaard (1993) this ichnogenus is known to characterize shallow-water hard substrates.

The ichnoassemblage evolution reflects changes in ecological parameters (e.g. mainly due to the sedimentation rate). From the sequence of biologic events that occurred in the Foz da Fonte surface, one can infer the succession of the infaunal communities that colonized the hard substrate.

Gastrochaenolites are generally shallow-water trace fossils. Where individuals are crowded and dominate the assemblage only a few metres of water may be inferred (Bromley, 1992). In the Neogene of the Mediterranean, areas affected by *Gastrochaenolites torpedo* structures, produced by the bivalve *Lithophaga lithophaga*, are restricted to 1–2 m depth (Kleemann, 1973).

Although in Foz da Fonte the distribution of borings is patchy and the boring density does not exceed 250 borings per square meter, *Lithophaga* may have been the agent of intense bioerosion in the area. However, the population densities obtained here were far too low for overcrowding and intraspecific competition to be a probable influence and source of mortality.

Kleemann (1973) recorded abundances of 100 animals/0.0625 m^2 for *L. lithophaga* on the Mediterranean coasts of former Yugoslavia, which resulted in space competition, neighbouring shell erosion and stenomorphism of *Gastrochaenolites* borings. In Foz da Fonte, *Gastrochaenolites lapidicus* structures do not intersect those of *Gastrochaenolites torpedo*, showing a phobotaxic behaviour of the bivalves involved. Occasionally some *G. lapidicus* cut-cross epilithic bivalve shells encrusting *G. torpedo* or show evidences of infestation of empty *G. torpedo* borings (Fig. 8). The further colonization of the substrate by polychaete worms produces *Trypanites* structures inside *Gastrochaenolites* borings. This colonization implies a certain period of time during which neither important erosion, nor major deposition, took place.

The physical properties of the substrate and the sedimentation environment, namely sediment input, control this ichnofacies, which depends on lithified, exposed substrates. This trace fossil association may be related to the *Entobia* subichnofacies (MacEachern et al., 2007) of Bromley and Asgaard (1993) which in turn is assignable to the *Trypanites* ichnofacies of Frey and Seilacher (1980). This ichnofacies characterized by domichnial borings of worms (*Trypanites*), bivalves (*Gastrochaenolites*), cirripedes (*Rogerella*) and sponges (*Entobia*) formed in shoreline rocks or in lithified limestone hard surfaces on shallow seabeds.

The cirriped borings *Rogerella*, which show a patchy and restrict distribution, occur exclusively on the external part of the platform. Alignment of the *Rogerella* borings observed on this specific area of the hardground could be induced by the polarity of food supply direction due to currents (rheotropic orientation), which cause individuals to be clumped in the more favourable areas of the habitat. The preferred orientation is with the food gathering apparatus facing the current. Pemberton and Frey (1984) maintain that food resources and feeding adaptations are among the most important parameters constraining population dispersion.

The scarcity of epilithobiont remains attached to the surface is clearly related to the strong erosion associated with planar hard surfaces, as suggested by the shallowness of *Gastrochaenolites* truncated borings (Santos et al., 2008).

6.2. Comparison with other Portuguese Neogene rocky-shore communities

Santos et al. (2008) studied four Miocene hardgrounds in the Algarve (S Portugal: Sagres, Arrifão, Oura and Cacela), which are also interpreted as erosional transgressive surfaces associated with important bioerosion activity. However, there are some differences that distinguish these hardgrounds from the one at Foz da Fonte with respect to ichnodiversity and boring density.

Probably due to a better preservation, the Foz da Fonte hard substrate shows a more diversified ichnoassemblage with the presence of *Gastrochaenolites* and other ichnotaxa such as *Entobia*, *Caulostrepsis*, *Trypanites* and *Rogerella*, contrasting with the low ichnodiversity exhibited by southern Portuguese hard substrates. *Trypanites* and *Rogerella* borings are, for the first time, recognized in hardground surfaces of the western Atlantic façade of Iberia. Moreover, the diversity of *Gastrochaenolites* ichnospecies identified (*Gastrochaenolites torpedo*, *Gastrochaenolites lapidicus* and *Gastrochaenolites ornatus*) is higher in Foz da Fonte than in any other southern Portuguese localities, including the Oura surface, which is the Algarvian locality with higher *Gastrochaenolites* ichnodiversity (*G. torpedo*, *G. turbinatus* and *Gastrochaenolites* isp.) (Santos et al., 2008; Cachão et al., 2009). In all the other localities, due to poor preservation, only *Gastrochaenolites* isp. structures where identified.

Entobia and *Gastrochaenolites* borings are the only two ichnotaxa that are present in both Foz da Fonte and all the Southern Portuguese hard substrates, with exception of *Entobia* on the Oura site. Epilithobiont remains are scarce in all these localities. The Foz da Fonte locality is the only one that presents some epilithobiont diversity. In the south, Cacela is the only site where it is possible to observe a few encrusted oysters. In all the others epilithobiont remains are missing.

However, regarding the bioerosion density, the density of *Gastrochaenolites* is lower at Foz da Fonte (only 250 borings per m^2) than on the Arrifão (955 specimens per m^2) and Oura (300 specimens per m^2) rocky surfaces, although in all the cases the distribution is patchy (Santos et al., 2008; Cachão et al., 2009).

6.3. Palaeoenvironmental reconstruction

At Foz da Fonte, the observed ichnological succession appears to record repeated events of marine erosion. The cross-cutting relationships among borings indicate repeated events of erosion, encrustation and re-boring of the surface (Fig. 8).

In the Early Miocene, during the initial stage of the transgression, the emerged Cretaceous sedimentary sequence was eroded, forming a wave cut platform. The exposed Cretaceous limestone surface was rapidly and densely colonized by Miocene boring organisms. In these initial conditions wave energy is high enough to prevent sedimentation and encrusting organisms from settling and overgrowing the borings (Bromley, 1975).

The sequence of events leading to the formation of the rocky surface and its later bioerosion are reconstructed as follows (Fig. 9):

1. Cenomanian/Turonian to Early Miocene erosion of the emerged Cretaceous sedimentary sequence and formation of the limestone surface (Fig. 9.1–2).
2. In Miocene times, an initial shallow-water phase during marine flooding allowed colonization of submerged hardground by sponges (producing *Entobia*), sipunculid worms (producing *Trypanites*) and a dense population of boring bivalves producing *Gastrochaenolites torpedo* (probably *Lithophaga* sp. bivalves) and *Gastrochaenolites lapidicus* structures (Fig. 9.3).
3. The erosion and bioerosion of the surface continues leading to the obliteration of the upper half of the previous bioerosion structures (Fig. 9.4).
4. With the development of the transgression, water depth increases, resulting in the inhibition of the *Gastrochaenolites torpedo* producers and allowing the colonization by encrusting organisms such as *Pycnodonte* bivalves, balanomorph crustaceans and colonial corals (Fig. 9.5).
5. Abrasion and bioerosion continues smoothing the bioeroded surface, and tearing away some right valves of the *Pycnodonte* shells (Fig. 9.6). In the external part of the platform (seaward) shallow *Caulostrepsis* worm borings and *Rogerella* acrothoracican cirriped borings were produced.

The boring activity was terminated by the burial of the hardground surface under sediment in a shallow marine environment. This assumption is based upon the marine fossil assemblage present in the sediments above the surface and the absence of mineral staining – indicating subaerial exposure – on the surface itself or on the walls of the borings. The overlying terrigenous sediment was deposited rapidly, forming a homogeneous layer completely sealing the underlying bioeroded surface.

6.4. Tectonic linkages and structural analysis

The bioeroded surface culminates a significantly long stratigraphic gap (hiatus) spanning the interval from the Cretaceous to the Miocene during which break-up of the Cretaceous limestone beds and karstification occurred.

In situ bored lithified substrates are the better fossiliferous evidence for: 1) a near-shore marine palaeoenvironment allows drawing a coastline in its near vicinity and, 2) sedimentary omission or starvation that normally accompanies the fast inland migration of the coastal line during transgressions.

Thus Foz da Fonte Miocene bioerosion of Cretaceous limestones clearly demonstrates that a rocky-shore line existed in this location during middle Burdigalian times, and, thus, that a sector of the southern Setúbal Península was already uplifted and emerged at this stage. This emergent topographic relief is related to salt dome deformation formed, probably, as late as Palaeogene times. Recognition of the bioeroded hard substrate and dating reported here, makes the interpretation of the vertical tectonic disturbance in this region as the most probable.

7. Conclusions

During Early Miocene times (middle Burdigalian) the Western part of Iberia, namely the Arrábida region, was affected by, at least, one marine transgression. This is recorded at Foz da Fonte in the conspicuous bioerosion structures produced by marine organisms evidencing the existence of an ancient wave cut platform. The presence of these bioerosion trace fossils together with attached epifauna is evidence of a transgressive surface and corresponds to an ancient marine hard substrate community associated with sedimentary omission or starvation that normally accompanies the fast inland migration of the coastal line during transgressions. The main conclusions of this study can be summarized as follows:

1) The borings represent an *in situ* rocky substrate community of Miocene bivalves, sponges, barnacles and worms colonizing a Cretaceous limestone wave cut platform corresponding to a very shallow marine rocky substrate with a negligible sedimentation rate.

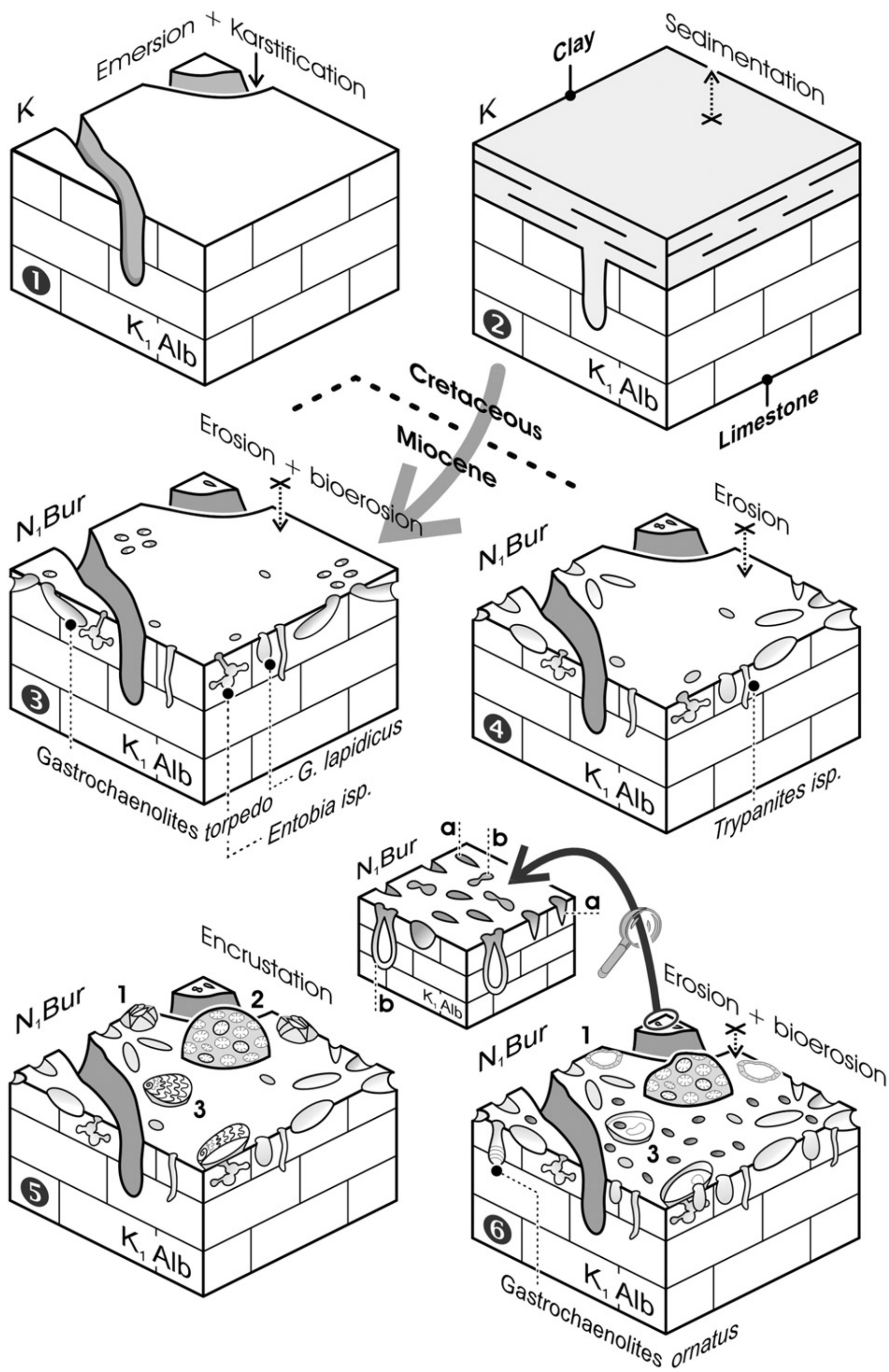


Fig. 9. Sequence of formation and palaeoenvironmental interpretation diagram of the Foz da Fonte bioeroded hardground. Bioerosion structures: a—*Rogerella* isp.; b—*Caulostrepsis* isp.; Encrusting organisms: 1—Barnacles; 2—Colonial corals; 3—Oysters; K_1Alb—Lower Cretaceous, Albian; N_1Bur—Miocene, Burdigalian. Age symbols and stage abbreviations after Harland et al., (1989).

2) Bivalve borings *Gastrochaenolites* are the dominant trace fossils in the studied outcrop. The highly energetic marine environment here could explain the low diversity of trace fossils and encrusting biota.
3) This trace fossil assemblage can be related to the *Entobia* subichnofacies of the *Trypanites* ichnofacies, which is recurrent worldwide on Neogene rocky shores.
4) The observed spatial and sequential relationship of bioerosion structures allows the reconstruction of a succession of bioerosion ichnocoenoses from a sponge-dominated community (represented by *Entobia* and *Trypanites*) to a bivalve-dominated community (represented by *Gastrochaenolites*) and finally by cirriped acrothoracic-dominated community (represented by *Caulostrepsis* and *Rogerella*).
5) From Tectonic point a view, the recognition of the Foz da Fonte bioeroded transgressive surface is crucial for establishing the presence of a vertical tectonic disturbance in this region prior to the middle Burdigalian, associated to the emplacement of a salt dome and a volcanic sill.

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References

Antunes, M.T., Elderfield, H., Legoinha, P., Pais, J., 1995. Datações isotópicas com Sr do Miocénico do flanco Sul da Serra da Arrábida. Comissão Instituto Geológico e Mineiro 81, 73–78.

Antunes, M.T., Legoinha, P., Cunha, P.P., Pais, J., 2000. High resolution stratigraphy and Miocene facies correlation in Lisbon and Setúbal Peninsula (Lower Tagus basin, Portugal). Ciências da Terra 14, 183–190.

Benner, J.S., Ekdale, A.A., de Gibert, J.M., 2004. Macroborings (*Gastrochaenolites*) in Lower Ordovician hardgrounds of Utah: sedimentologic, paleoecologic, and evolutionary implications. Palaios 19, 543–550.

Bertling, M., 1999. Taphonomy of trace fossils at omission surfaces (Middle Triassic, East Germany). Palaegeography, Palaeoclimatology, Palaeoecology 149, 27–40.

Bown, P., 1998. Calcareous Nannofossil Biostratigraphy. Chapman & Hall. 314 pp.

Brett, C.E., 1998. Sequence stratigraphy, paleoecology, and evolution: biotic clues and responses to sea-level fl uctuations. Palaios 13, 241–262.

Brett, C.E., Brookfield, M.E., 1984. Morphology, faunas and genesis of Ordovician hardgrounds from Southern Ontario, Canada. Palaegeography, Palaeoclimatology, Palaeoecology 46, 233–290.

Bromley, R.G., 1975. Trace fossil at omission surfaces. In: Frey, R.W. (Ed.), The Study of Trace Fossils. Springer-Verlag, New York, pp. 399–428.

Bromley, R.G., 1992. Bioerosion: eating rocks for fun and profit. In: Mapples, C.G., West, R.R. (Eds.), Trace Fossils. Short Courses in Paleontology, n°5. A Publication of the Paleontological Association, pp. 121–129.

Bromley, R.G., Asgaard, U., 1993. Endolithic community replacement on a Pliocene rocky coast. Ichnos 2, 93–116.

Bromley, R.G., Ekdale, A.A., 1986. Composite ichnofabrics and tiering burrows. Geological Magazine 123, 59–65.

Bronn, H.G., 1837–1838. Lethaia geognostica oder Abbildungen und Beschreibungen der für die Gebirgs–Formationen bezeichnendsten versteinerungen. Schweizerbart, Stuttgart. 1350 pp.

Cachão, M., Moita, T., 2000. *Coccolithus pelagicus*, a productivity proxy related to moderate fronts off Western Iberia. Marine Micropaleontology 39, 131–155.

Cachão, M., da Silva, C.M., Santos, A., Domèmech, R., Martinell, J., Mayoral, E., 2009. The bioeroded megasurface of Oura (Algarve, south Portugal): implications for the Neogene stratigraphy and tectonic evolution of southwest Iberia. Facies 55, 213–225.

Choffat, P., 1950. Géologie du Cénozoique du Portugal. Comunicações Serviços Geológicos Portugal XXX (Suplem.). 182 pp.

da Silva, C.M., Cachão, M., Martinell, J., Domènech, R., 1999. Bioerosional evidence of rocky palaeoshores in the Neogene of Portugal: environmental and stratigraphical significance. Bulletin of the Geological Society of Denmark 45, 156–160.

Ekdale, A.A., Bromley, R.G., 2001. Bioerosional innovation for living in carbonate hardgrounds in the Early Ordovician of Sweden. Lethaia 34, 1–12.

Ekdale, A.A., Bromley, R.G., Pemberton, S.G., 1984. Ichnology: Trace Fossils in Sedimentology and Stratigraphy (Short Course 15). Society of Economic Paleontologists and Mineralogists, Tulsa, Oklahoma. 317 pp.

Frey, R.W., Seilacher, A., 1980. Uniformity in marine invertebrate ichnology. Lethaia 13, 183–207.

Fürsich, F.T., Oschmann, W., Jaitly, A.K., Singh, I.B., 1991. Faunal response to transgressive–regressive cycles: examples from the Jurassic of Western India. Palaeogeography, Palaeoclimatology, Palaeoecology 85, 149–159.

Ghibaudo, G., Grandesso, P., Massari, F., Uchman, A., 1996. Use of trace fossils in delineating sequence stratigraphyc surfaces (Tertiary Venetian basin, Northeastern Italy). Palaeogeography, Palaeoclimatology, Palaeoecology 120, 261–279.

Goldring, R., Kaźmierczak, J., 1974. Ecological succession in intraformational hardground formation. Palaeontology 17 (4), 949–962.

Harland, W.B., Armstrong, R.L., Craig, L.E., Smith, A.G., Smith, D.G., 1989. A Geologic Time Scale. Cambridge Univ Press, Cambridge. 279 pp.

Johnson, M.E., 1988a. Why are ancient rocky shores so uncommon? Journal of Geology 96, 469–480.

Johnson, M.E., 1988b. Hunting for ancient rocky shores. Journal of Geological Education 36, 147–154.

Johnson, M.E., 2006. Uniformitarianism as a guide to rocky-shore ecosystems in the geological record. Canadian Journal of Earth Sciences 43, 1119–1147.

Johnson, M.E., Baarli, B.G., 1987. Encrusting corals on a latest Ordovician to earliest Silurian rocky shore, Southwest Hudson Bay, Manitoba, Canada. Geology 15, 15–17.

Johnson, M.E., Baarli, B.G., 1999. Diversification of rocky-shore biotas through geologic time. Géobios 32, 257–273.

Johnson, M.E., Ledesma-Vázquez, J., 1999. Biological zonation on a rocky-shore boulder deposit: Upper Pleistocene Bahia San Antonio (Baja California Sur, Mexico). Palaios 14, 569–584.

Johnson, M.E., Rong, J., Kershaw, S., 1998. Calibrating Silurian eustasy against the erosion and burial of coastal paleotopography. In: Landing, E., Johnson, M.E. (Eds.), Silurian Cycles—Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic, and Tectonic Changes, New York State Museum, Bulletin 491, pp. 3–13.

Kelly, P., Bromley, R.G., 1984. Ichnological nomenclature of clavate borings. Palaeontology 27 (4), 793–807.

Kendal, C.G.St., Schlager, W., 1981. Carbonates and relative changes in sea level. Marine Geology 44, 181–212.

Kleemann, K.H., 1973. Der gesteinsabbau durch Ätzmuscheln an kalkküsten. Oecologia 13, 377–395.

Kullberg, J.C., 2000. Evolução tectónica mesozóica da Bacia Lusitaniana. PhD thesis, Universidade Nova de Lisboa, Portugal, 361 pp. (Unpublish).

Kullberg, J.C., Rocha, R.B., 1991. Evidências tectónicas da existência de uma estrutura diapírica entre o Cabo Espichel e Sesimbra. Abst. III Congresso Nacional Geologia, Coimbra. 116 pp.

Kullberg, M.C., Kullberg, J.C., Terrinha, P., 2000. Tectónica da Cadeia da Arrábida. Tectónica das regiões de Sintra e Arrábida. Memórias Geociências, 2. Museu Nacional História Natural Universidade Lisboa, pp. 35–84.

Kullberg, J.C., Rocha, R.B., Soares, A.F., Frey, J., Terrinha, P., Callapez, P., Martins, L., 2006a. A Bacia Lusitaniana: Estratigrafia, Paleogeografia e Tectónica. In: Dias, R., Araújo, A., Terrinha, P., Kullberg, J.C. (Eds.), Geologia de Portugal no contexto da Ibéria, Universidade de Évora, pp. 317–368.

Kullberg, J.C., Terrinha, P., Pais, J., Reis, R.P., Legoinha, P., 2006b. Arrábida e Sintra: dois exemplos de tectónica pós-rifting da Bacia Lusitaniana. In: Dias, R., Araújo, A., Terrinha, P., Kullberg, J.C. (Eds.), Geologia de Portugal no contexto da Ibéria, Universidade de Évora, pp. 369–396.

MacEachern, J.A., Pemberton, S.G., Gingras, M.K., Bann, K.L., 2007. The Ichnofacies Paradigm: A fifty-year retrospective. In: Miller III, W. (Ed.), Trace Fossils. Concepts, Problems, Prospects. Elsevier, Amsterdam, pp. 52–77.

Mägdefrau, K., 1932. Über einige Bohrgänge aus dem unteren Muschelkalk von Jena. Paläontologische Zeitschrift 14, 150–160.

Manuppella, G., Antunes, M.T., Pais, J., Ármalo, M.M., Rey, J., 1999. Carta Geológica de Portugal (Notícia Explicativa) 1:50 000, Folha 38-B Setúbal. Instituto Geológico e Mineiro, Portugal. 143 pp.

Manuppella, G., (coord.), 1994. Carta Geológica de Portugal à escala 1:50 000, Folha 38-B Setúbal. Instituto Geológico e Mineiro, Portugal.

Miranda, R., Valadares, V., Azevedo, M.R., Terrinha, P., Mata, J., Gaspar, M., Kullberg, J.C., Nogueira, C., Ribeiro, C., Monteiro, J.F., 2006. New geochronological and geochimical data on the Late Cretaceous alkaline intrusions of the West Iberian Margin. Abstracts IV Congresso Nacional Geologia, Évora, pp. 129–132.

Miranda, R., Valadares, V., Terrinha, P., Mata, J., Azevedo, M.R., Gaspar, M., Kullberg, J.C., Ribeiro, C., 2009. Age constraints on the Late Cretaceous alkaline magmatism on the West Iberian Margin. Cretaceous Research 30, 575–586.

Palmer, T.J., 1982. Cambrian to Cretaceous changes in hardground communities. Lethaia 15, 309–323.

Pemberton, S.G., Frey, R.W., 1984. Quantitative methods in ichnology: spatial distribution among populations. Lethaia 17, 33–49.

Perch-Nielsen, K., 1989. Cenozoic calcareous nannofossils. In: Bolli, H., Saunders, J.B., Perch-Nielsen, K. (Eds.), Plankton Stratigraphy. Cambridge University Press, I, pp. 427–554.

Pirazzoli, P.A., Stiros, S.C., Laborel, J., Laborel-Deguen, F., Arnold, M., Papageorgious, S., Morhange, C., 1994. Late-Holocene shoreline changes related to palaeoseismic events in the Ionian Islands, Greece. Holocene 4, 397–405.

Plag, H.-P., 2006. Recent relative sea-level trends: an attempt to quantify the forcing factors. Philosophical Transactions of the Royal Society of London. Series A. Physical Sciences and Engineering 364, 821–844.

Radwanski, A., 1970. Dependence of rock-borers and burrowers on the environmental conditions within the Tortonian littoral zone of Southern Poland. In: Crimes, T.P., Harper, J.C. (Eds.), Trace Fossils 2: Geological Journal Special Issues 9, pp. 227–264.

Rasmussen, E.S., Lomholt, S., Andersen, C., Vejbæk, O.V., 1998. Aspects of the structural evolution of the Lusitanian Basin in Portugal and the shelf and slope area offshore Portugal. Tectonophysics 300, 199–225.

Ribeiro, A., Antunes, M.T., Ferreira, P., Rocha, R.B., Soares, A.F., Zbyszewski, G., Moitinho de Almeida, F., Carvalho, D., Monteiro, J.H., 1979. Introduction à la Géologie generale du Portugal. Serviços Geológicos de Portugal. 114 pp.

Ribeiro, A., Kullberg, M.C., Kullberg, J.C., Manuppella, G., Phipps, S., 1990. A review of Alpine tectonics in Portugal: foreland detachment in basement and cover rocks. Tectonophysics 184, 357–366.

Santos, A., Mayoral, E., 2007. Bioerosion vs colonisation on Bivalvia: a case study from the Upper Miocene of Cacela (Southeastern Portugal). Geobios 41, 43–60.

Santos, A., Mayoral, E., da Silva, C.M., Cachão, M., Domènech, R., Martinell, J., 2008. Trace fossil assemblages on Miocene rocky shores of southern Iberia. In: Wisshak, M., Tapanila, L. (Eds.), Current Developments in Bioerosion. Springer-Verlag, Berlin Heidelberg, pp. 431–450.

Taylor, P.D., Wilson, M.A., 2003. Palaeoecology and evolution of marine hard substrate communities. Earth-Science Reviews 62, 1–103.

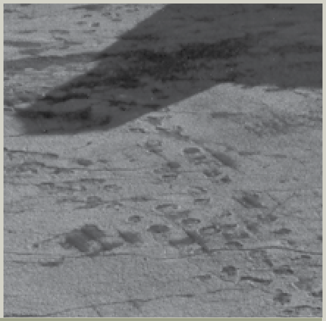
Voigt, E., 1959. Die ökologische Bedeutung der Hartgründe (Hardgrounds) in der oberen kreide. Paläeontologische Zeitschrift 33, 129–147.

Wilson, M.A., 1985. Disturbance and ecologic succession in an Upper Ordovician cobble dwelling hardground fauna. Science 228, 575–577.

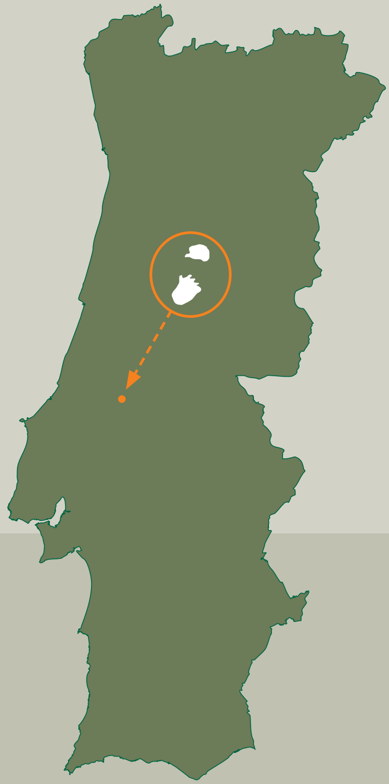
Wilson, M.A., 1987. Ecological dynamics on pebbles, cobbles and boulders. Palaios 2, 594–599.

Wilson, M.A., Palmer, T.J., 1992. Hardgrounds and hardground faunas. University of Wales, Aberystwyth, Institute of Earth Studies Publications 9, 1–131.

Wilson, R.C.L., Hiscott, R.N., Willis, M.G., Gradstein, F.M., 1989. The Lusitanian Basin of West Central Portugal: Mesozoic and Tertiary tectonic, stratigraphic, and subsidence history. In: Tankard, A.J., Balkwill, H. (Eds.), Extensional Tectonics and Stratigraphy of the North Atlantic MarginsAAPG Memoir, 46, pp. 341–361.



Pedreira do Galinha



Idade: 168 Ma (Jurássico Médio)

Tipos de fósseis: Pegadas (impressões)

Dinossáurios: Saurópodes

Sumário:

- Vinte pistas de saurópodes de diferentes dimensões, alguns com 3 a 4 m do solo à anca
- Duas das mais longas pistas conhecidas no mundo (140 a 150 m de extensão)
- Pegadas bem conservadas com marcas de dedos e morfologias únicas
- Pistas largas de um grupo primitivo de saurópodes que apresentavam um proeminente dedo polegar na mão
- Pistas que sugerem velocidades de deslocação entre 4 e 5 km/h

A João Carvalho, a J. P. Martins Barata e a Rui Galinha

Quem visita as serras de Aire e Candeeiros pode encontrar testemunhos da passagem de dinossáurios conservados nas superfícies das camadas de calcários que constituem estes relevos. Foi o que aconteceu a João Carvalho quando, em Julho de 1994, reconheceu a existência de rastos destes animais na Pedreira do Galinha, situada na localidade denominada Bairro, entre Torres Novas e Fátima. Ao procurar fósseis de invertebrados, encontrou o que na altura era o mais longo trilho de saurópode jamais visto.

Rui Galinha, responsável pela Empresa Alfredo Francisco Galinha, Lda., que laborava na pedreira conhecida como a Pedreira do Galinha, colaborou no estudo preliminar das pegadas, permitindo o acesso em segurança a este local e facilitando a limpeza da laje (Fig. 1). A área foi observada em pormenor, as pegadas foram desenhadas e as várias distâncias entre elas foram medidas e registadas (por exemplo, o passo, a passada e o ângulo de passo). A avaliação científica, pedagógica e cultural deste icnótopo, apresentada pelo Museu Nacional de História Natural, foi o início de um complexo processo que visou a salvaguarda desta ocorrência e que culminou com a sua classificação, em 1996, como Monumento Natural. Este local é oficialmente designado por Monumento Natural das Pegadas de Dinossáurios Ourém – Torres Novas (DR nº 12/96, de 22 de Outubro), mas também é conhecido por Monumento Natural das Pegadas de Dinossáurios da Serra de Aire.

Figura 1.
Vista geral do icnótopo da Pedreira do Galinha (Jurássico Médio, Fátima).

Quando observada no início da manhã, com luz rasante à superfície, a laje com as pegadas parece uma área com sedimento recentemente pisado pelos dinossáurios que deixaram para trás os seus rastos. Trata-se de uma superfície com cerca de 40 000 m^2 e centenas de pegadas de saurópodes, organizadas em, pelo menos, vinte pistas.

A superfície exposta pela actividade da antiga pedreira é o topo de uma camada de calcário que há cerca de 168 Ma, constituía o fundo de uma laguna litoral confinada e de profundidade muito reduzida, com sedimentos finos carbonatados. Esta lama foi pisada por vários dinossáurios e conservou muitas das suas pegadas, bem como restos de bivalves, de gastrópodes e de outros invertebrados. Estão ali preservadas algumas das mais longas pistas de saurópodes conhecidas no mundo (uma tem 147 m de extensão), e as pegadas de saurópodes do Jurássico Médio mais bem conservadas que se conhecem. De facto, o seu estado de conservação é excelente, notando-se, inclusivamente, um rebordo formado pelo sedimento que foi afastado devido ao peso do animal (Fig. 2). A boa definição das marcas revela a morfologia dos pés e das mãos que as produziram.

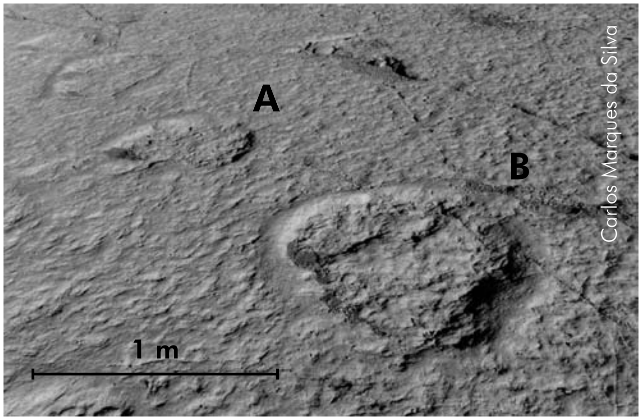


Figura 2
As impressões da mão direita (**A**) e do pé direito (**B**) do saurópode que produziu a pista 1 preservada no icnótopo da Pedreira do Galinha (Jurássico Médio, Fátima) revelam um rebordo formado pelo sedimento que foi afastado devido ao peso do animal.

Foi feito um levantamento topográfico da área da jazida a fim de se obter um mapa sobre o qual dez dos vinte trilhos reconhecidos foram desenhados (Fig. 3). Este trabalho foi executado por Carlos Antunes do Departamento de Matemática da Faculdade de Ciências da Universidade de Lisboa, em Fevereiro e Março de 2000. Uma malha quadrada de vinte metros de lado foi implementada através de pequenas marcas cravadas na rocha, perfeitamente identificadas, e que assinalam os vértices da malha. Este referencial serve para auxiliar o estudo paleontológico e os trabalhos de restauro da laje necessários à sua conservação.

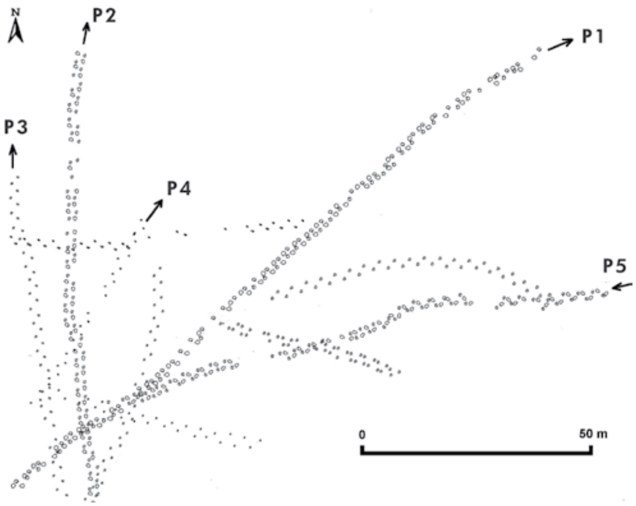


Figura 3.
Mapa com os dez principais trilhos de saurópodes do icnótopo da Pedreira do Galinha (Jurássico Médio, Fátima). [2, 3]

A pista do saurópode de maiores dimensões aqui identificada (P1) pode ser seguida ao longo de 147 metros: é constituída por impressões das mãos e dos pés, ambas com rotação para o exterior do rasto e, embora possam aparecer parcialmente sobrepostas num ou noutro ponto da pista, existe uma distância que as separa, chegando, por vezes, aos 56 cm (Fig. 4). Os pés deixaram impressões ovais e sem marcas de dedos, com 95 cm de comprimento por cerca de 70 cm de largura (Figs. 2, 4). O comprimento das marcas do pé deste saurópode permite calcular que teria cerca de 3,8 m desde o solo à anca. A profundidade destes icnitos é variável, apresentando uma zona menos profunda que separa a área afundada pelos dedos ao tocarem no solo e a que resulta do apoio parcial do resto do pé formado pelos metatarsos. As marcas mais nítidas das mãos que têm forma de crescente e não estão parcialmente apagadas pela sobreposição das ovais, têm 40 cm de comprimento por 75 cm de largura e revelam um arco metacarpal (arco formado pela posição dos metacarpos) suavemente arqueado, com os bordos medial e lateral arredondados (Fig. 4A,B); são muito grandes em relação às marcas dos pés. Na maioria das pistas de saurópodes conhecidas no registo mundial, as marcas dos pés são cerca de três a seis vezes maiores do que as das mãos. No entanto, nesta pista constatamos que a área da marca do pé é duas vezes a área da marca da mão. Muitas das marcas de mãos na pista 1 apresentam uma impressão longa e estreita, virada para trás, o que lhes confere uma morfologia diferente de todas as outras conhecidas no registo mundial. O valor da largura interna da pista é de cerca de 60 cm. O valor médio do

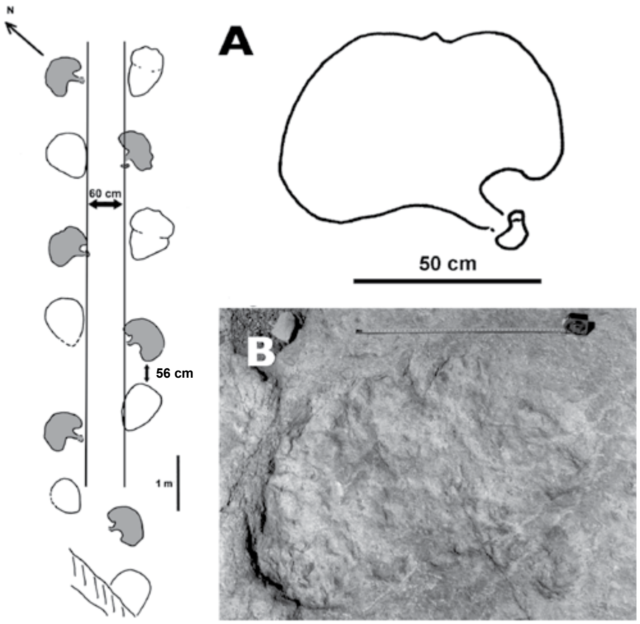
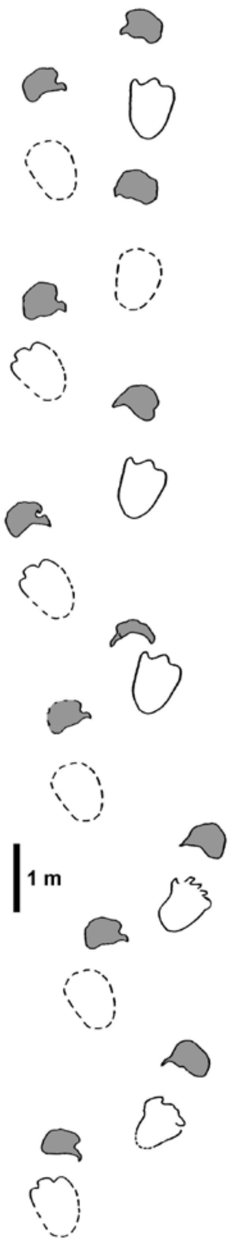


Figura 4.
Pista de saurópode (P1) no icnótopo da Pedreira do Galinha (Jurássico Médio, Fátima). As marcas das mãos estão a sombreado. Desenho (**A**) e fotografia (**B**) de uma marca de mão esquerda de saurópode com uma impressão fina que se dirige para trás e para o interior da pista. [2, 3]

passo é de 1,5 m e o da passada é de 3,1 m. Admite-se que este saurópode estaria a deslocar-se a uma velocidade estimada de 4 km/h.

A pista P5 do icnótopo da Pedreira do Galinha é igualmente extensa podendo ser seguida ao longo de 142 m; é também constituída por dois tipos de impressões, umas ovais e outras em forma de crescente, ambas com rotação para o exterior do rasto (Fig. 5). As marcas mais nítidas das mãos que não estão parcialmente apagadas pela sobreposição das ovais, têm 38 cm de comprimento por 58 cm de largura, apresentam o arco metacarpal suavemente arqueado, o bordo lateral arredondado e o medial com uma longa marca da garra do dedo I (16 cm de comprimento), com terminação pontiaguda e dirigida para o interior da pista (Fig. 5A, C). O contorno das marcas de mãos mais bem preservadas nesta pista revela evidências de quatro outros dedos. As marcas dos pés são mais compridas do que largas, têm 90 cm de comprimento por 60 cm de largura e apresentam impressões das garras dos dedos I e II dirigidas para a frente, dos dedos III e IV dirigidas em sentido lateral e uma possível marca do dedo V arredondada (Fig. 5B,D).



As impressões das mãos e dos pés que constituem as pistas P1 e P5 apresentam características que as distinguem de outros morfotipos de pegadas descritos no registo fóssil mundial. Deste modo, no Jurássico Médio português existe o registo de duas morfologias únicas de impressões de mãos e de pés de saurópode.

A área das marcas dos pés na pista P5 é duas vezes a área das marcas das mãos e o comprimento das marcas do pé deste saurópode permite inferir que teria cerca de 3,6 m do solo à anca. O valor da largura interna da pista é de cerca de 70 cm, o valor médio do passo é de 2,1 m e o da passada é de 3,1 m. Admite-se que este saurópode estaria a deslocar-se a uma velocidade estimada de 4 km/h.

Os estudos efectuados no icnótopo da Pedreira do Galinha indicam a passagem de outros saurópodes cujos membros posteriores teriam 3 a 4 m do solo à anca e que estariam a deslocar-se, dentro do caminhar, a uma velocidade estimada de 4 a 5 km/h.

Pistas largas como as pistas P1 e P5 da Pedreira do Galinha têm sido atribuídas a saurópodes do grupo dos titanossáurios, cujas mãos eram desprovidas de dedos e gar-

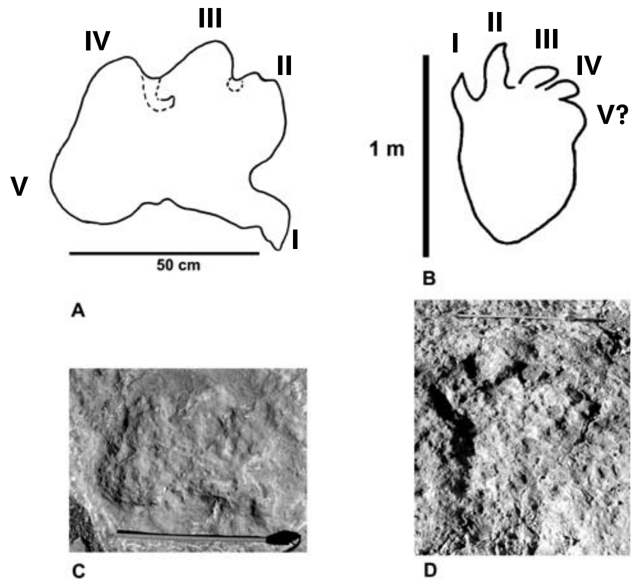


Figura 5.
Pista de saurópode (P5) no icnótopo da Pedreira do Galinha (Jurássico Médio, Fátima). [2, 3, 4] As marcas das mãos estão a sombreado. Desenho (**A**) e fotografia (**C**) de uma marca de mão esquerda com evidente marca da garra do dedo I e dos outros quatro dedos. Desenho (**B**) e fotografia (**D**) de uma marca de pé direito com evidências de garras dos dedos I e II dirigidas para a frente, dos dedos III e IV dirigidas em sentido lateral e uma possível marca do dedo V arredondada.

ras. Porém, as proeminentes marcas de dedos e da garra do dedo I que se observam nas impressões das mãos que constituem as pistas P1 e P5 (Figs. 4A,B e 5A,C) indicam que os dinossáurios que as produziram não pertenciam a este grupo e sugerem que pertencem a um grupo mais primitivo de saurópodes, cujas mãos estavam providas de dedos e de forte garra no dedo polegar.

Na Pedreira do Galinha para além de rastos de saurópodes formados pelas impressões das mãos e dos pés, existem algumas pistas incompletas constituídas, sobretudo, pelas impressões das mãos. Uma das pistas é constituída por marcas das mãos bem definidas e em forma de crescente, com 27 cm de comprimento por cerca de 45 cm de largura, bem como por vestígios das marcas dos dedos dos pés por corresponderem às zonas onde os pés fizeram maior pressão no solo (Fig. 6).

A descoberta e a descrição de pistas incompletas de saurópodes tem vindo a ser feita com alguma regularidade. Actualmente, a maioria dos paleontólogos pensa que se trata de conservação parcial das impressões, dado que as mãos, devido à sua menor área, podiam afundar-se no chão lamacento mais do que os pés, e por isso ficaram mais bem impressas nos sedimentos (Fig. 7). Estas pistas incompletas alertam os investigadores para a necessidade de se compreender, em primeiro lugar, os fenómenos que envolvem a sedimentação, conservação e a fossilização para, posteriormente, se efectuarem interpretações relacionadas com o comportamento dos animais.

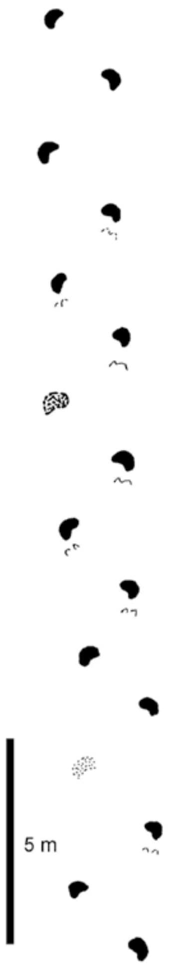


Figura 6.
Esquema de uma pista de saurópode constituída predominantemente por marcas de mãos no icnótopo da Pedreira do Galinha (Jurássico Médio, Fátima). [4]

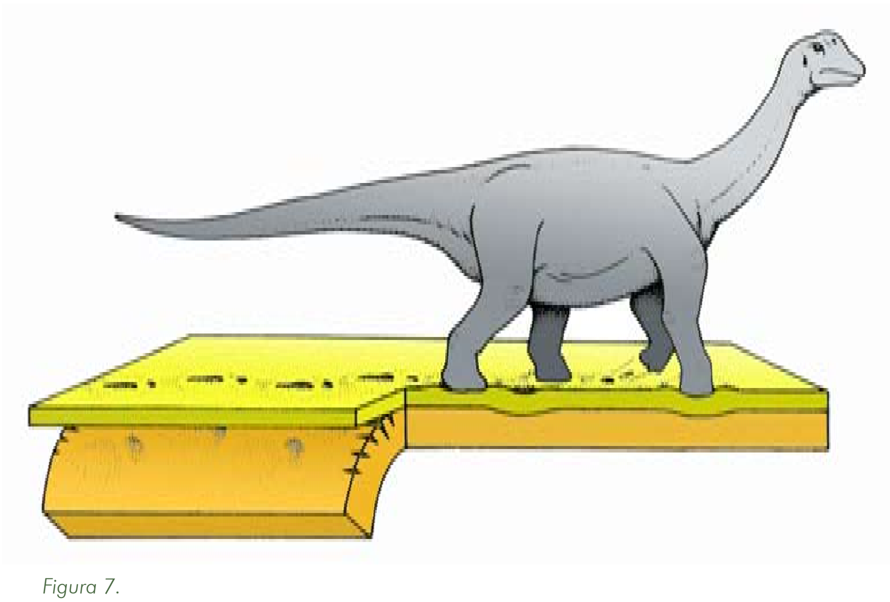


Figura 7.
A conservação diferencial das pegadas permite explicar a existência de pistas incompletas. As mãos dos saurópodes podiam enterrar-se mais do que os pés e, por isso, produzir, numa camada inferior, uma pista constituída predominantemente por marcas de mãos.

Vale de Meios

Idade	168 Ma (Jurássico Médio)
Tipos de fósseis	Pegadas (impressões)
Dinossáurios	Terópodes e saurópodes
Sumário	

- Centenas de pistas paralelas de terópodes
- Carnívoros com 2 a 3 metros do solo à anca
- Pistas de terópodes que sugerem velocidades de deslocação entre 4 e 7 km/h
- Pelo menos duas pistas de saurópodes

A António Frazão, a Luís Ferreira e a Maria da Glória Araújo

Ao percorrermos as serras de Aire e Candeeiros podemos observar vários aspectos relacionados com a exploração dos calcários. Existem muitas pedreiras em actividade, outras em processo de recuperação da paisagem e outras, especiais, que nos mostram antigas áreas alagadiças por onde dinossáurios passaram há cerca de 168 milhões de anos. É o caso de Vale de Meios e de Algar dos Potes, dois locais onde pedreiras puseram a descoberto lajes de calcário com pegadas de dinossáurio. Estas duas jazidas situam-se a NE da povoação de Pé da Pedreira, no concelho de Santarém.

Em Vale de Meios uma espectacular área de 11 400 m^2 permite-nos identificar inúmeros rastos entre milhares de impressões tridáctilas de dinossáurios, na grande maioria paralelos entre si (Fig. 1). O número de pegadas e de pistas, bem como a sua extensão, tem vindo a aumentar à medida que prosseguem quer a extracção de pedra, quer as operações de limpeza da laje e as observações de pormenor ali em curso. Há centenas de trilhos de terópodes de diferentes dimensões que seguiam segundo uma direcção preferencial NW-SE. Também pelo menos duas pistas deixadas por grandes saurópodes cruzam uma série de pistas de terópodes de pequena a média dimensão.

Figura 1.
Vista de uma zona da jazida de Vale de Meios numa altura em que a exploração pôs a descoberto as pegadas (Jurássico Médio, Santarém).

A maior parte das pegadas de terópodes está muito bem conservada e algumas apresentam uma definição de contornos extraordinária (Fig. 2). Através do seu estudo é possível obter uma imensa quantidade de informação paleoanatómica e paleoecológica sobre os dinossáurios carnívoros do Jurássico Médio, altura em que estes seres ainda estavam numa fase inicial da sua evolução. Podemos conhecer a morfologia dos pés dos dinossáurios que deixaram estas pegadas e estudar aspectos da sua locomoção e comportamento.

Figura 2.
Pegadas (impressões) de terópodes na jazida de Vale de Meios (Jurássico Médio, Santarém).

Figura 3.
Pista de terópode na jazida de Vale de Meios (Jurássico Médio, Santarém). [2]

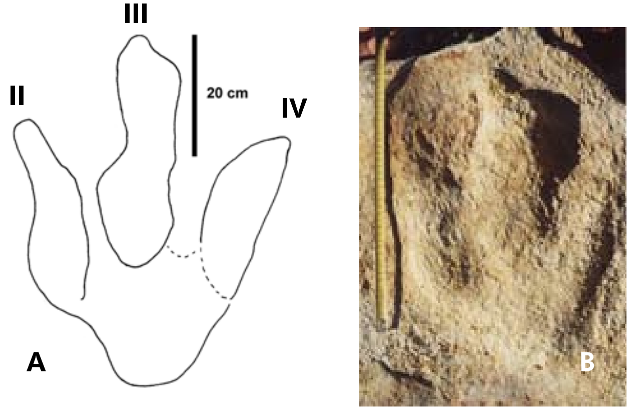


Figura 4.
Aspecto des pegadas de terópodes na jazida de Algar dos Potes (Jurássico Médio, Santarém). **A**: Esquema de impressão de um pé tridáctilo; **B**: Contramolde de impressão que se encontra em relevo na base da camada que cobria a laje com as impressões. [2]

Uma das pistas tem 10 m de extensão e é constituída por oito impressões tridáctilas e mesaxónicas (isto é, com o dedo central mais desenvolvido) com 58 cm de comprimento por 50 cm de largura, marcas de três dedos com cerca de 10 cm de largura e lados paralelos, encontrando-se ainda preenchidas por finas capas de sedimento. O comprimento das marcas do pé deste terópode permite calcular que teria cerca de 2,8 m desde o solo à anca. O valor médio do passo é de 1,4 m e o da passada de 2,8 m e admite-se que este terópode estaria a deslocar-se a uma velocidade estimada de 4 a 5 km/h. O valor médio do ângulo de passo nesta pista é de 152°.

Uma outra pista é constituída por três pegadas tridáctilas, com 43 cm de comprimento por 31 cm de largura e marcas finas de dedos: a do dedo III tem os lados paralelos e 5 cm de largura, bem como uma impressão fina e pontiaguda deixada por uma garra (Fig. 3). O comprimento das marcas do pé deste terópode permite calcular que teria cerca de 2,1 m desde o solo à anca. O único valor de passada registado foi de 2,8 m; os dois valores de passo obtidos são de cerca de 1,4 m. Admite-se que este terópode estaria a deslocar-se a uma velocidade estimada entre 6 e 7 km/h. O valor do ângulo de passo nesta pista é de cerca de 170°, o que reflecte uma locomoção caracterizada pela colocação dos pés sobre o eixo médio de deslocação. Para as pegadas ficarem assim alinhadas o dinossáurio movimentava a anca de modo a que as pernas rodassem para o interior da pista, ao mesmo tempo que a cauda se dirigia em sentido contrário para manter a estabilidade durante a locomoção. Este alinhamento das pegadas é uma característica da maioria dos rastos aqui conservados.

A superfície da laje que se observa em Algar dos Potes apresenta impressões tridáctilas, em geral em bom estado de conservação (Fig. 4A). Algumas têm 48 cm de comprimento por 37 cm de largura, com uma reentrância no lado interno do calcanhar (o que o torna assimétrico), marcas de dedos longos com os lados paralelos e pontiagudos na zona distal, tendo os dedos II e IV comprimentos semelhantes e sendo o IV rectilíneo.

Na área onde se reconhecem estas impressões tridáctilas também existem alguns blocos que revelam os seus contramoldes (Fig. 4B). Estes blocos pertencem à camada de calcário que cobria as impressões e que foi transformada em pedra de calçada, na sequência dos trabalhos da pedreira que ali funcionou.

Figura 5.
Trabalho de campo na jazida de Vale de Meios (Jurássico Médio, Santarém) para efectuar a descrição das pegadas e pistas.

As pegadas observadas nestas jazidas foram deixadas por dezenas de terópodes num terreno horizontal, inundado e lamacento, possivelmente junto às margens de uma laguna litoral.

Os estudos efectuados indicam que existiram nesta área, no Jurássico Médio, terópodes cujos membros posteriores teriam 2 a 3 m do solo à anca e que estariam a deslocar-se dentro do caminhar, a uma velocidade estimada de 4 a 7 km/h.

A morfologia geral de algumas destas pegadas tridáctilas é semelhante à de pegadas do icnótopo do Cabo Mondego, atribuídas ao tipo *Megalosauripus*. Assim, ao atribuirmos algumas pegadas tridáctilas das jazidas de Vale de Meios e de Algar dos Potes ao tipo *Megalosauripus*, estamos a admitir que dinossáurios carnívoros semelhantes a *Megalosaurus* deixaram alguns destes trilhos.

O rasto de um saurópode de grandes dimensões testemunha que também os grandes herbívoros quadrúpedes frequentavam este local.

A continuação do estudo da jazida de Vale de Meios (Fig. 5) permitirá caracterizar as pegadas e as pistas de dinossários existentes e proporcionar informação paleobiológica e paleoambiental da área que é hoje o Maciço Calcário Estremenho, no Jurássico Médio.

À semelhança da Pedreira do Galinha, a jazida de Vale de Meios é um bem do nosso Património Natural de excepcional valor científico, pedagógico e cultural e encontra-se classificada como Imóvel de Interesse Municipal. Actualmente decorre o processo que visa a sua classificação como Monumento Natural, tendo em conta que:

1. é a maior e mais significativa jazida com pegadas de terópodes do Jurássico Médio da Península Ibérica, dada a elevada quantidade de pegadas existentes e o seu excelente estado de conservação;
2. é a única jazida no país onde é possível realizar estudos aprofundados sobre a paleoanatomia, locomoção e comportamento dos terópodes;
3. além de terópodes também revela a existência de saurópodes nesta área durante o Jurássico Médio.

Pedra da Mua

Idade: 145 Ma (Jurássico Superior)

Tipos de fósseis: Pegadas (impressões)

Dinossáurios: Terópodes e saurópodes

Sumário:

- Impressões de pés de saurópodes com marcas de dedos
- Sete pistas paralelas de pequenos saurópodes que constituíam uma manada
- Três pistas paralelas de grandes saurópodes que seguiam os mais pequenos
- Pista de um saurópode e de um terópode com passo irregular
- Terópode com cerca de 2 m do solo à anca

A Martin Lockley e a Christian Meyer

Os rastos de dinossáurio bem visíveis na arriba que limita a sul a Praia dos Lagosteiros que se situa a norte do Cabo Espichel (Sesimbra), cedo chamaram a atenção das populações locais. A comprová-lo parece estar a lenda de Nossa Senhora da Pedra da Mua, segundo a qual a Virgem Maria apareceu, em 1410, no topo do promontório, montando uma mula que ao subir pela laje conhecida por Pedra da Mua ou Mula, aí deixou o seu rasto. O Santuário de Nossa Senhora do Cabo ou da Pedra da Mua é constituído por vários elementos arquitectónicos, entre eles a Ermida da Memória que remonta ao início da peregrinação mariana nesta área. Num dos painéis de azulejo do interior da Ermida está representada a Virgem Maria com o Menino Jesus nos braços, sentada no dorso da mula, e um conjunto de marcas na laje representando o trilho do animal (Fig. 1). A existência no painel de azulejo, da representação de uma mula e de pegadas na laje desde o nível do mar até ao topo da arriba, são elementos importantes na lenda que parecem provar a sua relação com os rastos visíveis na arriba, os quais permaneceram até ao século XX sem serem reconhecidas como pistas de dinossáurio.

Nas lajes situadas entre o Cabo Espichel e a Praia dos Lagosteiros, atribuídas ao Jurássico Superior, conhecem-se várias superfícies com trilhos de dinossáurio. O icnótopo da Pedra da Mua é constituído por oito jazidas (camadas) com icnitos. A inclinação das lajes, de cerca de 40º N ou mesmo superior em alguns locais, obrigou a equipa de trabalho a escalar os afloramentos utilizando equipamento de segurança.

Há evidências da passagem de terópodes e de muitos saurópodes de grandes e de pequenas dimensões. A morfologia geral das pegadas tridáctilas e a estrutura dos rastos, com particular relevância para o elevado valor do ângulo do passo, sugerem que foram produzidas por terópodes (Fig. 2). Uma das pistas revela a existência de um carnívoro com cerca de 2 m do solo à anca.

A morfologia geral das impressões em crescente e das ovais, e a sua disposição ao longo dos trilhos, indicam que foram produzidas por saurópodes. Na camada 3 foram identificadas sete pistas paralelas de pequenos saurópodes que indicam uma velocidade de deslocação semelhante e um mesmo sentido de progressão (Fig. 3). Três pistas paralelas de saurópodes de maiores dimensões também são reconhecíveis nesta jazida: a pista que se encontra na área mais alta da laje cruza as pistas de saurópodes mais pequenos; as outras duas pistas estão mais abaixo. Curiosamente, tam-

Figura 1.
Painel de azulejos no interior da Ermida da Memória onde está representada a Virgem Maria sentada numa mula com o rasto que deixou para trás, rodeada por dois anjos, bem como videntes atraídos ao Cabo Espichel. (17)

bém foi reconhecida uma pista constituída apenas por marcas de uma das mãos (pista 9) que, evidentemente, reforça a importância de interpretar, em primeiro lugar, os aspectos da conservação das pegadas antes de inferir e especular sobre possíveis comportamentos.

As pistas dos pequenos saurópodes, paralelas e com uma orientação preferencial, indicam um grupo de juvenis ou sub-adultos que se deslocavam num mesmo sentido. Eram indivíduos cujos membros posteriores tinham 1,5 a 1,8 m de altura desde o solo à anca. Os três indivíduos de maiores dimensões tinham cerca de 2,8 m do solo à anca e também se deslocavam sensivelmente no mesmo sentido, constituindo, possivelmente, um outro grupo, tendo em conta as suas pistas paralelas. Os animais de menores dimensões viajavam a velocidades entre 3,6 e 5 km/h e os mais corpulentos entre 3,4 e 4,1 km/h.

Considera-se pouco provável que as pistas paralelas deste nível correspondam à passagem de indivíduos isolados sem qualquer relação entre si. Considera-se que terão passado no mesmo momento, pois a preservação das várias impressões é homogénea. O estudo de outros icnótopos conhecidos no mundo também revela que alguns dinossáurios viajavam em grupos constituídos por indivíduos semelhantes e do mesmo tamanho, à mesma velocidade e lado a lado, com o mesmo sentido de progressão.

Considera-se que esta jazida oferece um excelente testemunho de uma manada constituída, pelo menos, por sete pequenos saurópodes que se moviam para SE. Os dinossáurios maiores foram os últimos a passar

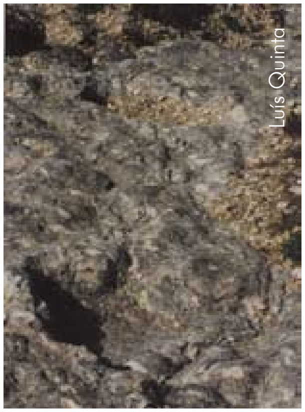


Figura 2.
Aspecto de uma pegada de terópode no icnótopo da Pedra da Mua (Jurássico Superior, Cabo Espichel).

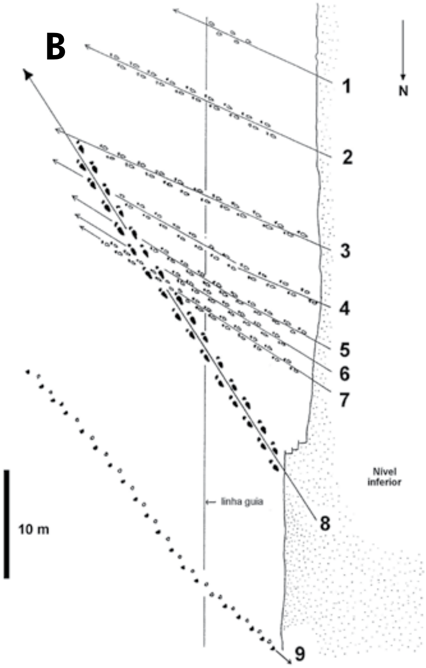


Figura 3.
Aspecto geral do icnótopo da Pedra da Mua (Jurássico Superior, Cabo Espichel).
A: Pormenor da área do nível 3 com pistas paralelas de saurópodes. **B**: Mapa com a representação das pistas dos pequenos saurópodes (1 a 7) e da pista do saurópode maior que as cruza (pista 8), bem como da pista constituída apenas por marcas de mãos (pista 9). [18]

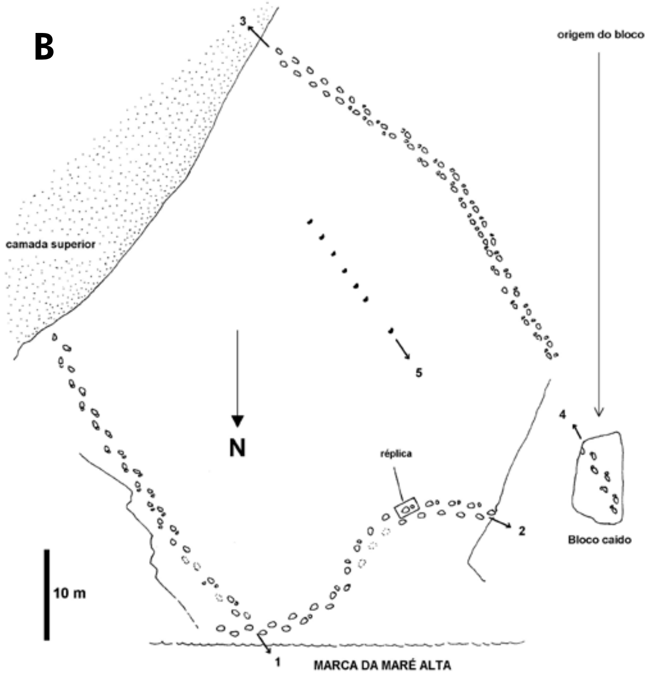


Figura 4.
Vista geral (**A**) e mapa (**B**) do nível 5 do icnótopo da Pedra da Mua (Jurássico Superior, Cabo Espichel). (19) **C**: Aspecto das pegadas da pista 1.

porque há evidências de que o saurópode que produziu a pista 8 pisou as pegadas dos mais pequenos (Fig. 3). Estas pistas paralelas constituiram o primeiro exemplo convincente de comportamento gregário nos saurópodes reconhecido numa jazida europeia, bem como o melhor testemunho conhecido entre animais tão pequenos.

O nível com pegadas de dinossáurio relacionado com a lenda da Nossa Senhora da Pedra da Mua, exibe cinco pistas de saurópodes (Fig. 4). São constituídas por impressões bem conservadas, profundas, com as margens verticais, algumas das quais com rebordos volumosos resultantes do afastamento do sedimento do centro da marca para a sua periferia, devido à pressão exercida pelos pés/mãos no solo (Fig. 4C).

A pista 2 foi deixada por um saurópode que se deslocou com uma rota bastante sinuosa (Fig. 4B) e está incompleta porque parte dos icnitos que se encontram mais perto do mar estão praticamente desgastados, devido à forte erosão provocada pelas vagas. As impressões ovais apresentam rebordos volumosos, têm cerca de 80 cm de comprimento por 58 cm de largura e revelam quatro marcas de dedos triangulares com a terminação aguçada, dirigidas para o exterior do rasto (Fig. 5). As impressões em forma de crescente têm cerca de 38 cm de largura por 18 cm de comprimento e não revelam vestígios de dedos. O comprimento das marcas do pé deste saurópode permite calcular que a altura dos seus membros posteriores desde o solo à anca, seria cerca de 3,2 m. A distância que separa os dois tipos de icnitos (distância interpar) é pequena, da ordem dos 15 cm; ocorrem por vezes sobreposições e ambas as marcas estão dirigidas para o exterior da pista. A área dos pés é cerca de quatro vezes a área das mãos. Foi produzido um molde de um conjunto de impressões de mão e de pé em excelente estado de conservação e que juntamente com uma réplica em gesso, fazem parte das colecções do Museu Nacional de História Natural da Universidade de Lisboa (Figs. 4B, 5).

A pista 3 do nível 5 do icnótopo da Pedra da Mua foi deixada por um saurópode de médias dimensões que coxeava, pois deixou pegadas espaçadas de modo irregular, isto é, os valores dos passos são, alternadamente, curtos e compridos.

Outro exemplo de um dinossáurio que coxeava é observável na laje que limita a sul a Praia do Cavalo – enseada a sul da Praia dos Lagosteiros.

Trata-se de pegadas tridáctilas, com cerca de 67 cm de comprimento, de um terópode cujos membros posteriores tinham, desde o solo à anca, uma altura de cerca de 3,3 m. Esta pista revela uma locomoção irregular e, neste caso, também não temos forma de saber a sua razão de ser. Era necessário encontrar pegadas que indicassem uma deformidade (por exemplo, um dedo a menos) para termos uma evidência. É provável que o animal tivesse a perna magoada e não o pé, ou, no caso do terópode, transportar algo pesado nas mandíbulas.

Esta é a mais espectacular das jazidas do concelho de Sesimbra, não só devido ao sítio privilegiado onde se encontra, mas também pela excelente conservação das impressões e relevância da informação paleoanatómica e paleoecológica que proporciona sobre os dinossáurios.

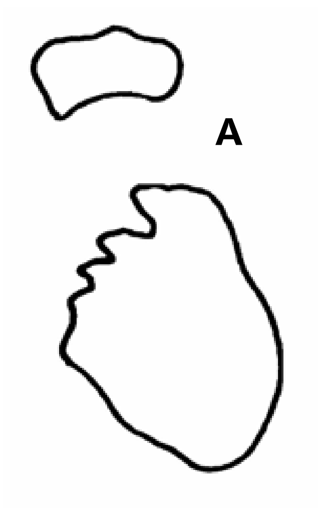


Figura 5.
Aplicação de látex num conjunto de pegadas de saurópode do nível 5 do icnótopo da Pedra da Mua (Jurássico Superior, Cabo Espichel). **A**: Impressão de pé de saurópode com quatro marcas de dedos triangulares, com a terminação aguçada e dirigidas para o exterior do rasto, e marca de mão. (19)

Lagosteiros

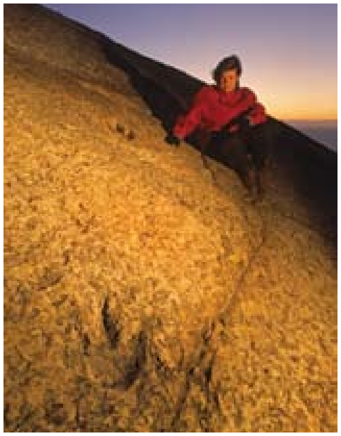
Idade	130-136 Ma (Cretácico Inferior)
Tipos de fósseis	Pegadas (impressões)
Dinossáurios	Terópodes e ornitópode
Sumário	• Pista de ornitópode, possivelmente de um iguanodontídeo • Pista de um pequeno terópode que estaria a deslocar-se a cerca de 14 km/h

A Miguel Telles Antunes

No topo da arriba que limita, pelo lado norte, a Praia de Lagosteiros, aflora uma camada de calcário castanho amarelado, inclinada para norte, em cuja superfície se observa um conjunto de pegadas – é o nível 3 do icnótopo de Lagosteiros. Os níveis 1 e 2 encontram-se na vertente sul do caminho que dá acesso à Praia dos Lagosteiros. É o icnótopo com pegadas de dinossáurio mais recente que se conhece na região.

O nível 3 de Lagosteiros revela uma pista extensa, constituída por impressões subcirculares (Fig. 1) que não fornecem informação sobre a morfologia dos pés do animal que a deixou. As pegadas subcirculares poderão ser interpretadas como o reflexo da pressão exercida pelos pés de um dinossáurio num estrato inferior ao da superfície pisada. Desta forma, o que nos é dado observar são as subimpressões.

Figura 1.
Vista de um segmento da pista mais longa do nível 3 do icnótopo de Lagosteiros (Cretácico Inferior, Cabo Espichel).



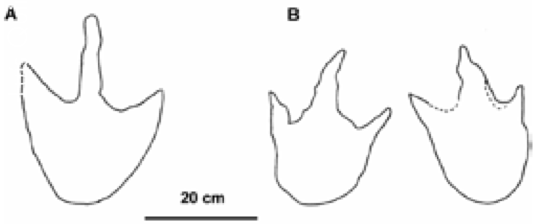


Figura 2.
Aspecto de impressões tridáctilas do nível 3 do icnótopo de Lagosteiros (Cretácico Inferior, Cabo Espichel).

Esta pista apresenta um valor de ângulo de passo de cerca de 155° característico de pistas de dinossáurios bípedes.

Para um dinossáurio deixar uma sequência de impressões alinhadas de pés, era obrigado a rodar a perna para o eixo de progressão, de modo a colocar um pé quase à frente do outro, sendo este tipo de movimento coerente com uma locomoção bípede. As pistas conhecidas no registo icnológico deixadas por saurópodes apresentam ângulos de passo da ordem dos 90 a 110°, enquanto que as pistas de animais bípedes são caracterizadas por ângulos de passo elevados, podendo observar-se pegadas quase alinhadas. No entanto, não é apenas o forte alinhamento destas impressões que sugere tratar-se de uma pista de um animal bípede. Tendo em conta que o estudo de outras jazidas permitiu evidenciar a relação estreita das impressões arredondadas, em pistas atribuíveis a dinossários bípedes do Cretácico, com as pegadas de iguanodontídeos, e que estes eram abundantes neste período, admite-se que esta pista de Lagosteiros tenha sido deixada por um destes dinossáurios bípedes herbívoros.

Também no nível 3 deste icnótopo há pegadas tridáctilas. As mais bem conservadas têm 28 a 33 cm de comprimento por 21 a 25 cm de largura, a terminação das marcas dos dedos é pontiaguda e a do dedo central apresenta-se ligeiramente curvada para o interior da pista (Fig. 2). Em algumas pegadas observa-se uma grande superfície plantar e marcas de dedos finos, interpretando-se como evidências de que a pegada sofreu deformação quando os sedimentos ainda estavam brandos (Fig. 2). A morfologia geral destas impressões indica terem sido terópodes que as produziram.

Neste icnótopo há evidências de dinossáurios carnívoros cujos membros posteriores tinham desde o solo à anca uma altura de 1,4 a 1,6 m e, uma das pistas sugere que um deles estaria a deslocar-se a cerca de 14 km/h. Este valor encontra-se dentro do intervalo correspondente ao trote e ao valor mais elevado conhecido no registo icnológico português, para a velocidade de um dinossáurio. Assim, as pegadas deste local testemunham a existência de dinossáurios bípedes de médias e pequenas dimensões, incluindo ornitópodes (possivelmente iguanodontídeos) e de terópodes.

Dinosaur track sites from Portugal: Scientific and cultural significance

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ABSTRACT - Dinosaur tracks in Portugal are known from Bajocian-Bathonian (Jurassic) through middle Cenomanian (Cretaceous) rocks. The Portuguese track record includes two outstanding Middle Jurassic track sites both in Central W Portugal: the Vale de Meios track site, showing dozens of parallel theropod trackways, and the Galinha site, where several long sauropod trackways can be seen. There are two other major areas with important dinosaur track sites: SW Algarve (S Portugal), Lower Cretaceous, and the Sesimbra region (Central W Portugal), Upper Jurassic-Lower Cretaceous. Huge track sites such as the Vale de Meios and Galinha sites can not be excavated and removed into museums; therefore, they must be preserved *in situ*, to be studied and visited in their original geological context. Track sites such as these are important not only for their scientific, ichnological, significance; they are also valuable for science popularization and to stimulate public interest for the preservation of the geological/palaeontological heritage. In Portugal, in 1996 and 1997, five dinosaur track sites have been declared natural monuments. In such sites it is possible to teach and show Palaeontology, as well as other aspects of Earth sciences in their original geological context, to children from different school levels and to a broad public with different scientific backgrounds. Educational programmes for school children and the general public are paramount in order to elucidate them about dinosaurs and their tracks, but also to improve their attitude towards the scientific and cultural value of this palaeontological ichnoheritage. Educational activities are essential to the success of geoconservation. They boost public awareness, which, in turn, is fundamental for the protection and valorisation of the geological and palaeontological heritage. When local communities are conscious of the scientific and cultural value of the natural heritage in their home region they become proud of it and this fact dramatically increases the odds of its effective protection. Nevertheless, up until now the Galinha track site is the only Portuguese track site prepared to receive visitors and to offer them palaeontological educational programmes.

Keywords: *Dinosaur, track sites, geoconservation, palaeontological ichnoheritage, exomuseum, educational centre, Portugal.*

INTRODUCTION

The oldest known scientific reference to dinosaur tracks in Portugal goes back to Gomes (1915-16). In this posthumous publication, Gomes reported the discovery, in 1884, of an Upper Jurassic bed containing dinosaur footprints at Pedra da Nau beach, Cabo Mondego (Cape Mondego) area, 2 km north of Buarcos (Figueira da Foz, Central Portugal) (fig. 1). This early report is one of the first references to the excavation and the study of dinosaur tracks in the world. The remarkable Cabo Mondego Upper Jurassic sequence encompasses the Aalenian-Bajocian stage boundary, making it a geosite of global significance, part of the World Geological Heritage (e.g. Pavia & Enay, 1997; Rodrigues *et al*., 2002).

Currently, in Portugal, dinosaur footprints are known from no less than twenty Middle Jurassic through Upper Cretaceous track sites. Many of these sites show several track levels, and their study yielded relevant data to the understanding of dinosaur palaeobiology. The Portuguese ichnological record includes some of the longest and best preserved sauropod trackways known worldwide, showing exceptionally preserved manus and pes impressions. One track site – Pedra da Mua, Upper Jurassic, Sesimbra region – yielded a compelling evidence of sauropod herding behaviour, including an example of herding among juvenile sauropod dinosaurs; other track sites – in the same location – revealed evidences of limping behaviour in dinosaurs; yet another – Vale de Meios track site – shows dozens of theropod tracks in a single track level, most of them belonging to animals travelling in the same direction (e.g. Dantas *et al*., 1994; Lockley & Santos, 1993; Lockley *et al*., 1994; Santos *et al*., 1994b, 2000a).

In addition to their outstanding scientific importance, some of these occurrences are privileged sites for geoscience popularization, having the potential to become exceptional geological and palaeontological education centres. Indeed, five of these sites have already been declared Natural Monuments under Portuguese law (namely Galinha, Carenque, Lagosteiros, Pedra da Mua and Avelino track

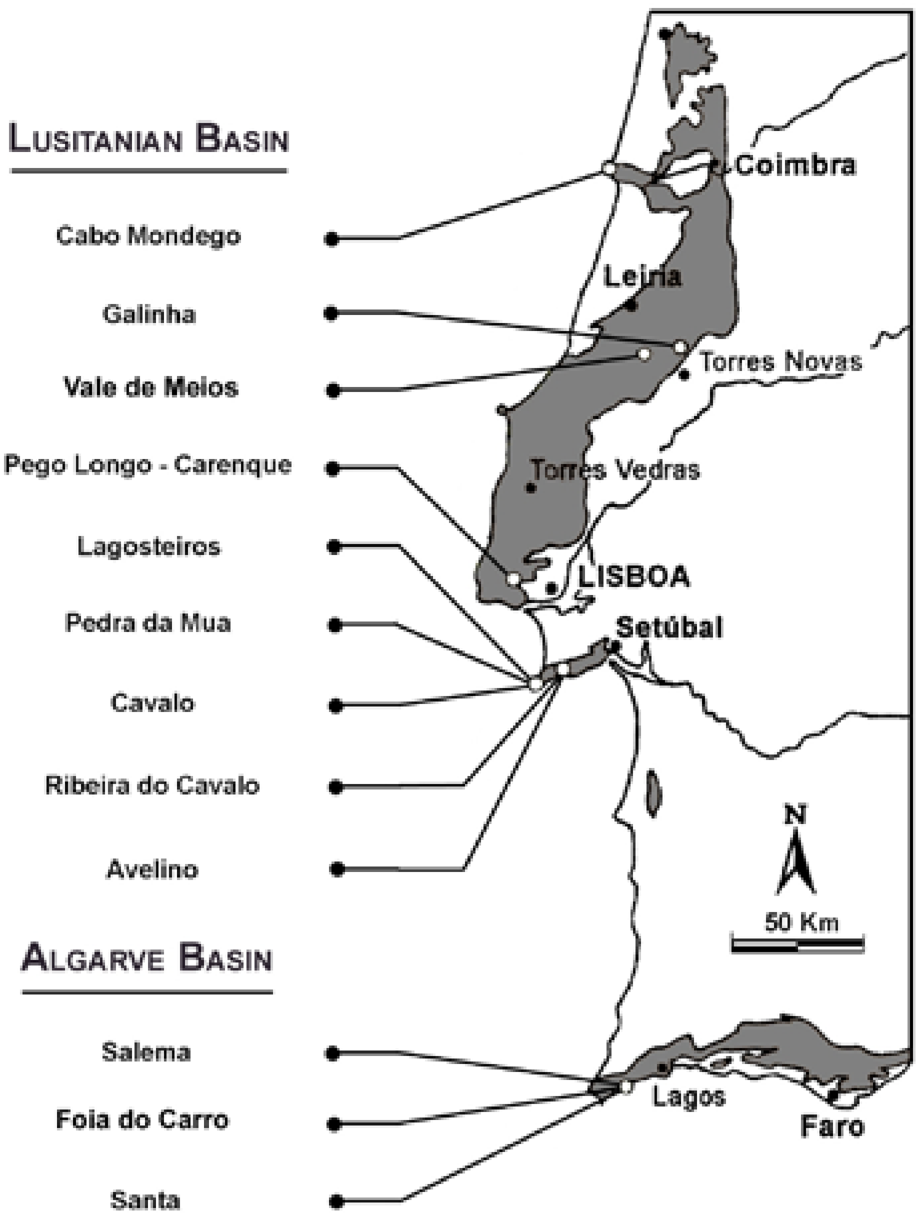


Figure 1 – Location of the main Portuguese tracksites in the Lusitanian (West Portugal) and Algarve Mesozoic basins (South Portugal).

sites) clearly reflecting their scientific, educational and cultural relevance. Nevertheless, so far, only the Galinha track site boasts operating educational programs and facilities capable of receiving and orientating visitors.

Fossils, the fossils of dinosaurs in particular, have always captured the public's interest. This characteristic of fossils may and should be used to enthral public attention and to focus it, also, on general geological aspects and on geoconservation issues. The Palaeontological Heritage is, therefore, a powerful driving force for geoconservation (Cachão *et al.*, 1999). The pride of local populations in their ichnoheritage fuels geoawereness and boosts their interest for geoconservation. This is crucial for effective site protection. Geoconservation-wise, this "geocultural identification" factor is more effective for the protection of the sites than the mere knowledge of their abstract scientific importance.

RELEVANT PORTUGUESE DINOSAUR TRACK SITES

Portuguese dinosaur track sites are mainly located in the Lusitanian basin (Western Portugal), and only three in the SW tip of the Algarve basin (S Portugal) (fig. 1). The Middle Jurassic track record is represented by Galinha and Vale de Meios track sites. Upper Jurassic dinosaur tracks are well documented at Figueira da Foz (Cabo Mondego track site), Sesimbra (Avelino and Ribeira do Cavalo track sites) and Cabo Espichel (Cavalo and Pedra da Mua track sites). In the Algarve basin it is known one Upper Jurassic track site at Foia do Carro bay, near Vila do Bispo village. Lower Cretaceous track sites are also known on the top of the cliff that borders the northern side of the small bay of Lagosteiros at Cabo Espichel (Lagosteiros track site) and near Óbidos

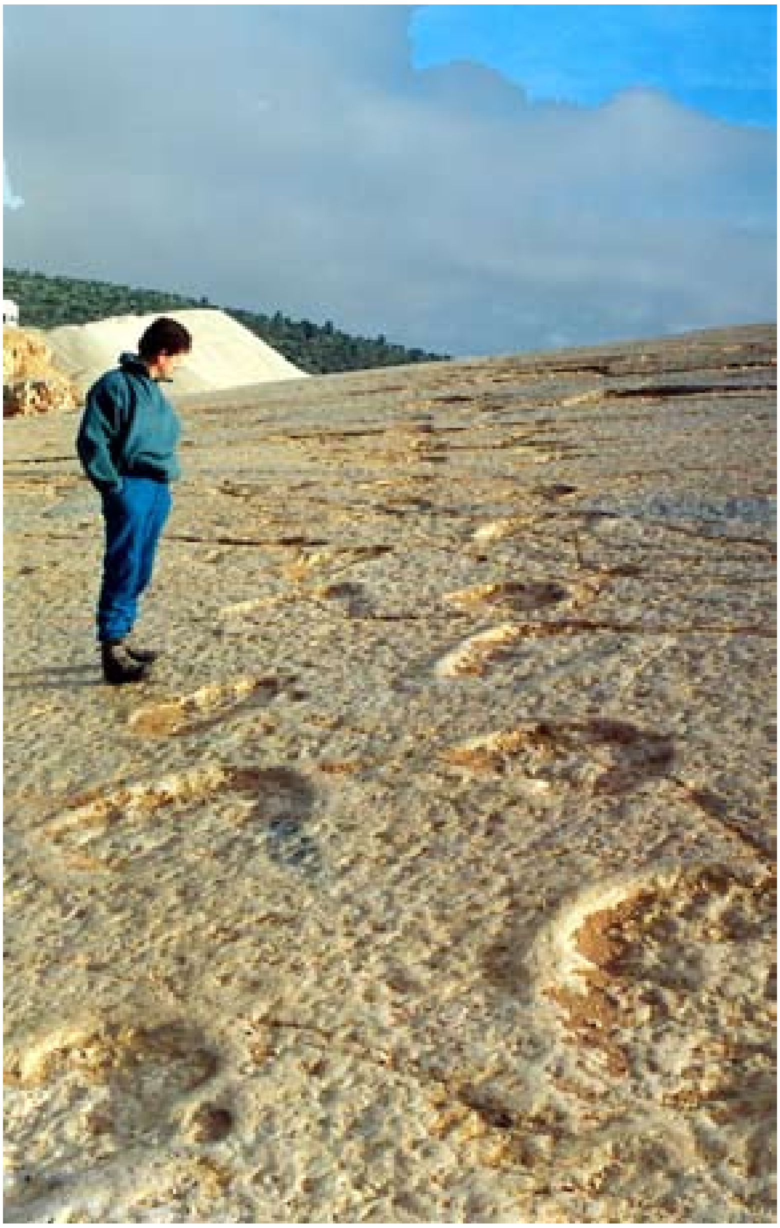


Figure 2 – Wide-gauge sauropod trackway at Galinha track site (Bajocian-Bathonian, Ourém - Torres Novas, Portugal).

(Olhos de Água track site, Mateus & Antunes, 2003) and in the Algarve: Salema and Santa track sites (Vila do Bispo). The Upper Cretaceous dinosaur track record is represented by the Carenque track site.

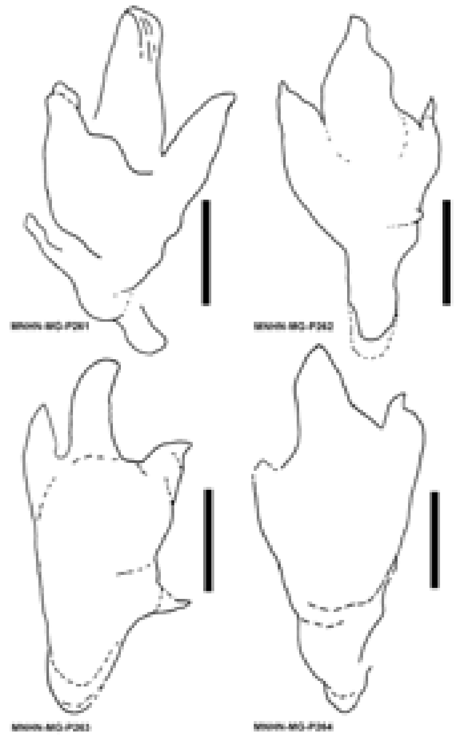
The Galinha track site

The Galinha track site is situated at a former limestone quarry near Fátima, on the eastern side of Serra d'Aire (West-Central Portugal), 120 km north of Lisbon. Several long sauropod trackways were discovered in the Galinha site in 1994 by João Carvalho, of the Torres Novas Speleological and Arqueological Society.

The tracks are located on 40.000 m^2 bedding surface, especially cleaned for their study with the cooperation of the former quarry owner Rui Galinha and the collaboration of the natural park Parque Natural das Serras d'Aire e Candeeiros (PNSAC). The site can be accessed without difficulty. The track level is located on a sub-horizontal bedding plane and displays long and visually spectacular wide-gauge sauropod trackways composed of sauropod pes and manus prints quite deeply impressed (Fig. 2) that can be easily observed from the high ground surrounding the former extracting area of the quarry. The wide-gauge long sauropod trackways are preserved on Middle Jurassic (Bajocian-Bathonian) limestones (Azeredo *et al*., 1995) and some consist of manus impressions only. In this track site are noticeable very well preserved sauropod manus and pes print morphologies (Santos *et al*., 1994b). Manus impressions reveal clear traces of digit I. The manus/pes area ratio is 1/2 and is different from ratios ranging up to 1/3 or 1/5 in other sauropod tracks suggesting a unique type of footprint (Santos *et al*., 1994b).

Figure 3 (left) – Theropod footprints at Vale de Meios track sites (Bathonian, Santarém, Portugal). Photograph by Luis Quinta.

Figure 4 (below) – Tetradactyl theropod footprints at Cabo Mondego track site (Oxfordian, Figueira da Foz, Portugal) (Lockley *et al*., 1996).



Since the Middle Jurassic dinosaur track record, and especially the sauropod track record, are poorly known (e.g. Clark *et al*., 2005; Clark & Barco Rodriguez, 1998; Day *et al*., 2004; Kvale *et al*., 2004; Lockley *et al*., 2007), the Galinha track site represents a considerable source of information on the Middle Jurassic sauropod palaeobiology.

The Vale de Meios track site

In 1998 several theropod dinosaur trackways were identified at Vale de Meios by Maria da Glória Araújo, Luís António Ferreira and António Frazão of the natural park Parque Natural das Serras d'Aire e Candeeiros (e.g. Santos *et al*., 2000a; Santos, 2003; Santos & Rodrigues, 2003). This site, situated near Alcanede village (Santarém, Central Portugal), is located in a working quarry extracting limestone of Bathonian age from the Maciço Calcário Estremenho (Estremenho Calcareous Massif) sedimentary formations. This track site, with an area of about 10.000 m^2, shows dozens of trackways (fig. 3), several of them displaying parallel displacement directions (Santos *et al*., 2000a; Santos, 2003; Santos & Rodrigues, 2003).

The Vale de Meios track site is presently under study. The ichnological survey is under way and the surface map of the site is currently being drawn in order to support its paleobiological and paleoecological interpretation. Preliminary research at Vale de Meios showed that it contains the most significant example of Middle Jurassic theropod footprints and trackways in Portugal. These trackways provide key evidence of theropod foot structure, locomotion and behaviour.

Theropod trackway-wise, the Middle Jurassic is a poorly known episode of geological history; therefore new discoveries are particularly important. The research at Vale de Meios track site will provide an important contribution to the knowledge of Middle Jurassic dinosaur communities and, therefore, its future preservation is crucial.

This site has good natural conditions to receive school children and the general public with little investment in basic infrastructures. The track site is easily accessible, and the tracks are located on a horizontal bedding surface.

The Cabo Mondego track site

This dinosaur track site is situated at Cabo Mondego, close to Figueira da Foz city. This was the first dinosaur track site discovered and studied in Portugal. At Cabo Mondego, Gomes (1915-1916) described large theropod tetradactyl footprints preserved as natural casts in Upper Jurassic deposits (Oxfordian). The morphology exhibited by these tracks is characterized by a long digit I mark and a metatarsal impression (fig. 4). These theropod tracks were attributed to the ichnospecies *Megalosauripus lusitanicum* (Lockley *et al*., 1996, 1998). At this track site, at least eight stratigraphic levels with theropod tracks were identified (Santos, 2003).

The Sesimbra - Espichel Region track sites

Between the locality of Sesimbra and the Cabo Espichel (cape Espichel) region, near Setúbal, five dinosaur track sites, comprising at least twenty different track levels, have been identified (fig. 1). These sites are: the Avelino and the Ribeira do Cavalo quarries, at Zambujal village, near Sesimbra, and the Cavalo, Pedra da Mua, and Lagosteiros sites in the Cabo Espichel area. Avelino, Pedra da Mua and Lagosteiros track sites were declared natural monuments on the basis of their scientific value, the exceptional natural scenery surrounding them and the potential to host educational programmes and pedestrian tours to visit dinosaur tracks.

At the Avelino track site, on Kimmeridgian limestones, narrow-gauge sauropod trackways were described (fig. 5), and assigned to *Parabrontopodus* isp. (Lockley & Santos, 1993). These trackways reveal the passage of five different sized sauropod trackmakers (pes prints length ranging from 30 to 100 cm) travelling separately in different directions.

Until the discovery of Vale de Meios track site, in 1998, well preserved theropod trackways where known only from the Ribeira do Cavalo quarry on a vertical bedding surface of Oxfordian-Kimmeridgian age (Lockley *et al*., 1992). Here, a manus dominated sauropod trackway with digit impressions was also described and a manus replica was made (Lockley *et al*., 1992). The site collapsed in 1995, due to lack of protection, destroying all the track records existing there (Santos *et al*., 1995).

In the coastal cliffs between Cabo Espichel and Lagosteiros bay (SW Setúbal) there are several dinosaur track levels in a stratigraphic sequence of Portlandian age (Upper Jurassic).

The Praia do Cavalo (Cavalo beach) is a track site located immediately to the South of Lagosteiros bay. In this site a trackway of a large theropod has been recorded and it was recognized a limping gait (Dantas *et al*., 1994).

At Lagosteiros bay, the cliff beneath the Sanctuary of Cabo Espichel, known as the Pedra da Mua track site, reveals at least eight levels with 38 sauropod trackways and two theropod trackways (Lockley *et al*., 1994). Sauropod trackways are all wide-gauge (*Brontopodus* type) and show well-preserved Upper Jurassic *Brontopodus* footprint specimens, showing four claw marks (Meyer *et al*., 1994). In one of the Pedra da Mua track levels, seven parallel sauropod trackways, showing the same travel direction, were recognized and described. These trackways are composed of footprints having similar sizes and depths (footprint length ranging from 38 to 46 cm). The analysis of these parallel trackways revealed that their producers were travelling at similar speeds (Lockley *et al*., 1994). Along these trackways three other trackways of larger animals, with footprint length ranging from 70 to 73 cm, progressing in the same direction may be observed (Lockley *et al*., 1994). This record represents the first compelling evidence of sauropod gregarious behaviour in the European track record and an interesting example of herd behaviour among young sauropods (Lockley *et al*., 1994). At Pedra da Mua track site there is a sauropod trackway with irregular pace length which is another example of a limping gait revealed in a dinosaur trackway (Dantas *et al*., 1994; Meyer *et al*., 1994).

The Lower Cretaceous (Hauterivian) Lagosteiros track site was discovered in 1971 on the top of the cliff north of Lagosteiros bay (Antunes, 1976). The most prominent feature of this track site is a long sequence of poorly preserved subcircular impressions, with similar size and depth, attributed to a bipedal animal, probably an ornithopod (e.g. Santos *et al*., 1992a; Santos, 2003). The site also shows several tridactyl impressions of small theropods, but only one short trackway is identifiable. In this theropod trackway it is possible to estimate a displacement speed value of about 14 km/h. This is the sole evidence of a fast moving dinosaur in the Portuguese track record (Santos, 2003).

Portuguese Lower Cretaceous track sites are also known from the coastal area of Óbidos (Central-West Portugal), 80 km north of Lisbon. Several theropod and ornithopod dinosaur trackways have been described from this site. For further information and location map see Mateus & Antunes (2003).

The Algarve Region track sites

In 1992 and 1995 the first dinosaur osteological and ichnological remains were found in the Algarve Mesozoic Basin at the Praia de Porto de Mós (Porto de Mós beach, Lagos), and at Praia da Salema (Salema beach), close to Vila do Bispo, respectively (Santos *et al*., 2000b,c; Santos, 2003). Since then, two more algarvian track sites were identified and documented.

At Porto de Mós beach, in a layer of Aptian age (Gargasian/Clansayesian, according to Rey 1983) dinosaur teeth and longitudinal sections of vertebras were recognized (Santos *et al.*, 2000b).

At the Salema track site two track levels were recognized on beds of Barremian age (e.g. Santos, 2003). The western track level reveals an ornithopod trackway. The best preserved footprint in this trackway displays the characteristic morphology of iguanodontid footprints. To the East of this slab, another track level was found with seven isolated theropod footprints.

Other Lower Cretaceous dinosaur track levels were found at Praia Santa (Santa beach), to the West of Salema

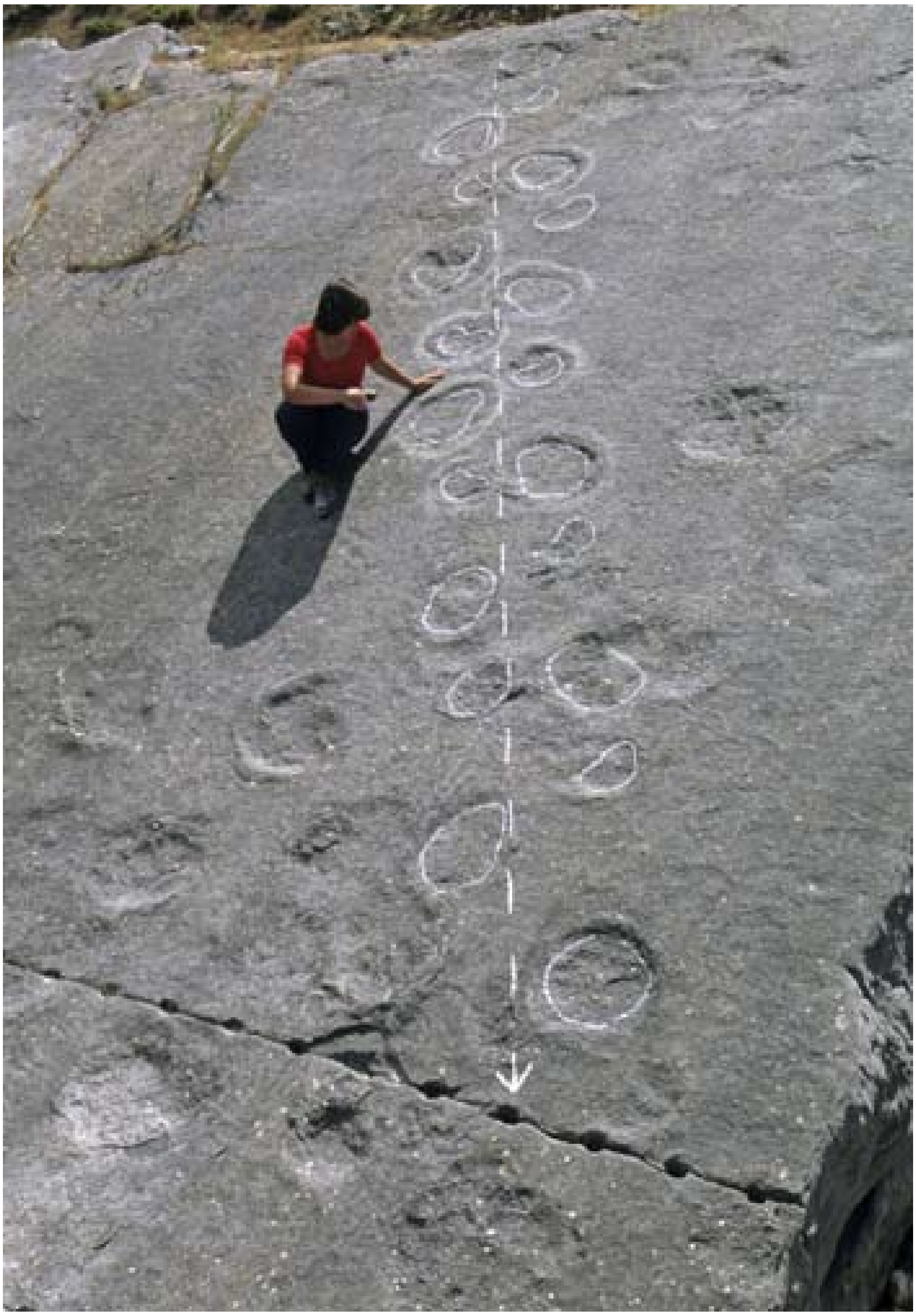


Figure 5 – Narrow-gauge sauropod trackway at Avelino track site (Upper Kimmeridgian, Sesimbra, Portugal). Photograph by Luis Quinta.

beach (Santos *et al*., 2000c). The main level revealed at least four bipedal trackways and isolated footprints. The well preserved prints in Santa track site reveal the characteristic iguanodontid morphology and their similarity with the prints attributed to *Iguanodontipus* isp. allows their assignment to this ichnogenus (Santos, 2003; Santos *et al*., 2000c). Until now, it was recognized the presence of iguanodontid and small unidentified theropods in the Lower Cretaceous of the Mesozoic Algarve basin (Santos *et al*., 2000b,c).

Sauropod trackways were also identified in two Upper Jurassic levels at Foia do Carro track site, close to Vila do Bispo village (e.g. Santos, 2003; Santos *et al*., 2000b).

The Carenque track site

The most recent dinosaur track site in Portugal is situated at Pego Longo (also known as Carenque), approximately 12 km NW of Lisbon, and it is Cenomanian in age (Upper Cretaceous). It was discovered in 1985 (Coke & Monteiro, 1986) and reveals theropod trackways and a single long trackway of a large bipedal animal. When first described, this trackway - with a total length of 127 m - was deemed the world's longest dinosaur trackway known (Santos *et al*., 1991, 1992a, b). This long bipedal dinosaur trackway is the main ichnological feature of the Carenque track site. The trackway is composed of a sequence of subcircular impressions without morphological details. It displays some unusual features of preservation, making it difficult to identify the trackmaker, however the pace angulation criterion suggests the attribution of this trackway to a bipedal dinosaur (Santos *et al*., 1992a).

PORTUGUESE DINOSAUR ICHNOHERITAGE

Pioneer campaign to preserve the ichonological heritage

The study of a long dinosaur trackway at Carenque (Pego Longo) track site initiated the pioneer task of protecting the Portuguese ichnoheritage (e.g. Cachão *et al*., 1998, 1999; Galopim de Carvalho, 1989, 1994, 1998; Galopim de Carvalho & Santos, 1992a,b; Galopim de Carvalho *et al*., 1996, 1998; Santos *et al*., 1991, 1992a,b, 1994a; Silva *et al*., 1998). The Carenque site was located exactly in the path of a motorway construction project and, therefore, destined to be destroyed. This circumstance started, in 1992, the so-called Battle of Carenque (Galopim de Carvalho, 1994). The scientific community started a joint effort to promote public awareness, to inform the public of the dinosaur footprints scientific and ichnoheritage potential. In the end, the involvement of the population and the local authorities was crucial for the geoconservation of this site.

In response to the overwhelming public interest on this site, the Portuguese Government was compelled to take action in order to protect the site from destruction. President Mário Soares, first, and the Portuguese Government, later, voted unanimously to preserve the site from destruction, by building a tunnel beneath it. In order to build the tunnel under the site, in 1993, the main Carenque trackway, as a protection measure, was covered. After the spur of the moment, unfortunately, the trackway remained covered and, therefore, unavailable for researchers and for the general public. The Carenque site, after all these years, still awaits a recovery programme.

In 1994 the discovery of Galinha track site was announced and its scientific importance and spectacular setting within a Natural Park gave it immediate international significance. Though having been discovered later, the Galinha track site was declared Natural Monument even before the classification of the Carenque site, in 1996. The Carenque site, now renamed Pego Longo track site, was declared Natural Monument in 1997 and became an international reference of a campaign to preserve Portuguese palaeontological heritage (Galopim de Carvalho, 1994).

In 1997, three track sites from the Sesimbra – Cabo Espichel region were also declared Natural Monuments: Pedra da Mua, Lagosteiros and Avelino sites. However, until now, the Galinha track site is the sole site prepared to receive visitors interested in learning about dinosaur footprints in Portugal.

The Galinha track site - an example of an educational centre

Since 1996, when the Galinha track site was classified as a Natural Monument, a geological, palaeontological and environmental education centre has been developed there. Indeed, to endorse and to protect the natural geoheritage it is necessary to create appropriate legislation but, more important, to promote educational programs for school children and the general public, in order to promote their geoawareness and improve their attitude towards the scientific and cultural values of this heritage (Santos *et al*., 2001; Cachão *et al*., 1999). The Galinha track site is equipped to receive visitors and in the last year alone nearly 50,000 people visited the site and took part in the site's educational activities. Visitors include school children, national tourists as well as tourists from all over the world, and national and international geosciences congresses participants. In the site, several educational activities are offered to the public that do not exist in other track sites, such as following a dinosaur trackway, measuring it, deducing the mode of displacement of the trackmaker - bipedal or quadruped - and calculating its size and speed.

The facilities and activities available on the site to receive visitors include a hall with a video room for the viewing of educational videos, guided tours and autonomous pedestrian trails with outdoor informative panels through out the entire track site perimeter (fig. 6), restrooms, picnic area, children playground, as well a dinoshop with educational products and publications on dinosaur tracks and nature issues.

Scientific data obtained from the study of the Galinha track site is periodically integrated in palaeontology popularization publications, making new scientific developments in dinosaur ichnology available for the general public. A natural size sauropod model is on display on the site, allowing the visitors to actually see how the presumed trackmakers looked like. A "Jurassic" botanical garden has been created, using plants of botanical groups known to having lived in Jurassic times, and a huge mural of the history of life on earth was painted there.

In addition to the sauropod trackways, in the Galinha site, several geological elements and structures may also be witnessed: e.g., limestones, stratification, faults, karst, minerals (calcite and pyrite) and invertebrate somatofossils (i.e., body fossils).

Dinosaurs have always fascinated young people. The track site may be used as an open air "class room" where dinosaurs and their tracks can be used to show how Geology, Physics, Chemistry, Biology, Ecology and even Mathematics may and should be used to analyse and understand palaeobiological issues. In the site it is possible to teach Palaeontology, as well as other geological disciplines, for different school and scientific levels. Several concepts can be combined in a single guided visit: earth history; palaeoenvironments; different types of geological structures and how they

Figure 6 – Autonomous pedestrian trails are supported by outdoor informative panels throughout the entire Galinha track site perimeter.

were formed; karst; sedimentary rocks (limestones) and their origin; environmental impact of human activities; possible ways of dealing with the negative impact of quarrying activities in the landscape.

The quantity and the quality of the dinosaur tracks preserved here allow us to understand life in past geological Eras and turn this site into a place of rare interest for environmental education, for promoting educational actions which may contribute to instil respect for nature and the natural heritage. All the aspects stated above, combined with an easy access to the track site, and a mild climate, give this place a high potential for tourism, and make it possible to use it as an open air museum, an "exomuseum".

Other sites and other activities

Several other dinosaur track sites in Portugal have high educational and tourist potential but, up until now, none of them is prepared to receive visitors and to be enjoyed by the general public all year round autonomously, as it is possible to do at the Galinha educational centre. However, public institutions such as the National Natural History Museum of Lisbon University as well as independent science associations regularly organize fieldtrips to these sites.

Another strategy that allows the general public to visit places where they can observe geological and paleontological features, namely dinosaur track sites such as those in the Algarve, is the programme "Geology in the summer". This programme is part of a national campaign which takes place every year during the summer period, from July until September, promoted by Agência Ciência Viva (Live Science Agency), the Portuguese national agency for scientific and technological culture. The activities of Ciência Viva are the contribution of the Portuguese Ministry of Science and Technology to the promotion of scientific culture among the Portuguese population.

The programme "Geology in the summer" started in 1998 and includes, every year, dozens of different geological activities, promoted by Portuguese universities, museums and independent science associations. Concerning Palaeontology, these activities comprise indoor activities in museums but mostly outdoor visits to fossiliferous sites guided by trained palaeontologists and geologists, nature walks to observe fossils and geological features *in situ*, and even city walks, e.g., the activity "Fossils on your door step" (Silva & Cachão, 1998), to observe and interpret fossils trapped in building material in Lisbon – fossils of rudists, corals, gastropods, invertebrate ichnofossils, etc., literally entombed within the stone used in buildings – and small outcrops still preserved within city limits. Another Geology in the Summer activity – GPS_Geologia por Satélite (GPS_Geology and Satelites) – encourages autonomous visits to track sites in the Sesimbra-Cabo Espichel region by giving the participants – in a specifically created web site (Silva, 2007) – the geographic coordinates of the track sites to be found with the aide of a personal GPS in a virtual geocache (or earthcache) mode. The web site also provides additional information about the outcrops and how to behave adequately in the field, in order to warrant a safe and meaningful visit and to promote geoawareness, ensuring the long term preservation of the track sites. The participants are asked to provide proof of their visit to the sites (by means of a digital photo taken on the spot) and receive, as a prize for their successful participation, additional information and educational materials produced by the National Natural History Museum and the Geology Department of the University of Lisbon.

In other European countries there are many track sites where the general public can observe dinosaur tracks and trackways in their geologic context.

Some of them are easily accessible places located along the shoreline, where the visitors may find dinosaur tracks as natural casts lying loose on the beach or preserved *in situ* on the bedding surfaces of cliffs, such as the sites along the south coast of the Isle of Wight in the UK (e.g. Martill, 2000).

The Ardley quarry, for example, in Oxfordshire in the UK, displays hundreds of dinosaur footprints but does not have public access and permission is required before visiting the site (Powell, 2003).

Other dinosaur track sites are linked to local museums. In these sites there are organized walking trails and interpretative panels that allow visitors to enlighten themselves about aspects of local geology and paleontology. This is the case of track sites such as Lavini di Marco in Italy (e.g. Avanzini, 2002), Asturias coastline and La Rioja province in Spain (e.g. García-Ramos *et al*., 2000; Moratalla *et al*., 1997), Isle of Skye in Scotland, UK (e.g. Clark *et al*., 2005).

An European dinosaur track site with a project similar to the Galinha exomuseum may be found at Münchehagen, near Hannover, in Germany (Dinosaurierpark Münchehagen). In this site dinosaur tracks are protected and are integrated in the museum as an outdoor museum.

Sites like the Courtedoux track site in northwestern Switzerland (e.g. Le Loeuff *et al*., 2006) and the Coisia track site (eastern France) also have scientific, educational and tourist potential to become outdoor museums.

Geoconservation – effective protection of the ichnoheritage at the Galinha exomuseum

Public interest on dinosaur track sites is high, as demonstrated by the high number of visitors to the Galinha site every year, therefore the impact of such natural occurrences is of paramount importance for geoeducation and for the local economy. The potential of the dinosaur track sites for educational tourism purposes represents an important economical resource to be used with the necessary precautions in order to prevent possible damages due to overexploitation and overexposure of the site.

Indeed, the potential of the Galinha site to attract high numbers of tourists, being located in close proximity to a popular destination for thousands of pilgrims and religious tourists (The Fátima Sanctuary), has already been demonstrated. This circumstance poses real management problems when dealing with an overwhelming number of visitors. In addition we must also consider the effects of the natural erosion of the track surface exposed to weather conditions.

The advantages of scientifically and culturally enjoying such an important natural occurrence imply, therefore, a responsible management capable of preserving the site. Indeed, the management of large track sites, especially regarding the preservation of track surfaces, presents several challenging geotechnical problems. Constructive geoconservation decisions have been made and measures will have to be taken soon to ensure that these track sites will be developed and managed as study sites for scientists, university and school students, and as attractive destinations for the general public from Portugal and from all over the world.

The Galinha track site and other dinosaur track sites have the potential to become a valuable asset to boost public awareness and scientific culture, places where local citizens and authorities bond with their local ichnoheritage, thus ensuring its real protection and adequate management. Indeed, to preserve and to value natural heritage in general it is required more than just protective legislation, it is necessary that the general public (including national politics and local authorities) understands its actual importance and long term implications. This way the fossil record may give an effective and essential contribution to environmental conservation.

FUTURE PERSPECTIVES

In normal circumstances, to observe dinosaur tracks in Portugal with scientific and educational support it is imperative to go to Galinha track site. This geoturistic destination has become so popular that schools and even private travel agencies regularly organize one day excursions, and some of them requiring travelling more than ten hours by bus, to go there and back, to visit the site. Such long travels have obvious inconveniences, especially for young children; therefore it would be useful to have other track sites in the country equipped – at least – with basic infrastructures to receive visitors.

For example, at Vale de Meios track site, 20-25 km SW of the Galinha quarry, deeply impressed tridactyl footprints can be easily followed on a horizontal bedding surface providing an unexpected and exciting opportunity to track Middle Jurassic theropods.

It would be equally useful to promote the accessibility to dinosaur track areas in different Portuguese regions such as the Sesimbra – Cabo Espichel and the SW Algarve area. As an immediate action, it would be of great public and educational service if local authorities and independent science associations could provide and maintain road and trekking signs to direct visitors to the track sites and the publication of educational material to support autonomous visitors.

Such a multiplication of ichnoturistic destinations would have several beneficial aspects to it, both economical and conservational. It would, for instance, boost local economy and geoawereness in other localities and, by providing alternative destinations, it would help prevent the overexploitation of Galinha track site.

However, even considering the possibility of adding new track sites to the Portuguese visitable sites list in the foreseeable future, on the short term it is essential to undertake direct actions – such as the periodical removal of gravel from the track surface along the visitors trail, in order to minimize erosion, and the overall consolidation of the track surface, namely by filling the existing cracks – for the future preservation of the Galinha track surface.

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REFERENCES

Antunes, M. T. 1976. Dinossáurios Eocretácicos de Lagosteiros. *Ciências da Terra*, 1: 1-35.

Avanzini, M. 2002. Il *Trentino dei dinosauri: i Lavini di Marco in Val Lagarina*. Provincia Autonoma di Trento, Servizio Geologico - Museo Tridentino di Scienze Naturali - Edizioni Osiride, Rovereto. 37 pp.

Azeredo, A. C., Ramalho, M. M., Santos, V. F. & Galopim de Carvalho, A. M. 1995. Calcários com pegadas de dinossáurios da Serra d'Aire: microfácies e paleoambientes. *Gaia*, 11: 1-6.

Cachão, M., Silva, C. M. da, Santos, V. F. & Galopim de Carvalho, A. M. 1999. Paleontological heritage as a driving force for geoconservation: the Portuguese experience: pp. 398-401. *In* Barettino, D., Vallejo, M. & Gallego, E. (eds.) *Towards the Balanced Management and Conservation of the Geological Heritage in the New Millenium.*, Soc. Geol. Espanha, Madrid.

Cachão, M., Silva, C. M. da, Santos, A., Santos, V. F. & Galopim de Carvalho, A. M. 1998. Património Paleontológico Português: critérios para a sua definição. Actas V Cong. Nac. Geol., *Comunic. Inst. Geol. Mineiro*, 84 (2): G22-G25.

Clark, D. L. & Barco Rodriguez, J. L. 1998. The first dinosaur trackway from the Valtos Sandstone Formation (Bathonian, Jurassic) of the Isle of Skye, Scotland, UK. *Geogaceta*, 24: 79-82.

Clark, D. L., Ross, D. A. & Booth, P. 2005. Dinosaur Tracks from the Kilmaluag Formation (Bathonian, Middle Jurassic) of Score Bay, Isle of Skye, Scotland, UK. *Ichnos*, 12: 93-104.

Coke, C. & Monteiro, P. B. 1986. Cartografia estrutural na região a ESE de Sintra. Estágio Científico F.C.U.L. 323p. (Unpublished Dissertation).

Dantas, P., Santos, V. F., Lockley, M. G. & Meyer, C. A. 1994. Footprint evidence for limping dinosaurs from the Upper Jurassic of Portugal. *Gaia*, 10: 43-48.

Day, J. J., Norman, D. B., Gale, A. S., Upchurch, P. & Powell, H. P. 2004. A Middle Jurassic Dinosaur Trackway Site from Oxfordshire, UK. *Palaeontology*, 47 (2): 319-348.

Galopim de Carvalho, A. M. 1989. Exomuseu de Geologia. *Encontro Nac. Ambiente, Turismo e Cultura*, Lisboa-Sintra, p. 4.

Galopim de Carvalho, A. M. 1994. *Dinossáurios e a batalha de Carenque*. Editorial Notícias, Lisboa, 291 pp.

Galopim de Carvalho, A. M. 1998. Geomonumentos: Uma reflexão sobre a sua classificação e enquadramento num projecto alargado de defesa e valorização do Património Natural. Actas V Cong. Nac. Geol., *Comunic. Inst. Geol. Mineiro*, 84 (2): G3.

Galopim de Carvalho, A. M. & Santos, V. F. 1992a. Sesimbra, um pólo importante para o conhecimento da história dos dinossáurios em Portugal. *Sesimbra Cultural*, 2: 6-9.

Galopim de Carvalho, A. M. & Santos, V. F. 1992b. Em defesa do ambiente natural. A jazida com pegadas de dinossáurios de Pego Longo (Carenque, Sintra). *III Enc. Nac. Ambiente*, Oeiras, p.7.

Galopim de Carvalho, A. M., Santos, V. F. & Moutinho, M. 1998. Musealização das jazidas portuguesas com pegadas de dinossáurios. Certezas e perspectivas. Abstracts of *Ist Internat. Meet. Dinosaur Paleobiology*, 1: 123-143.

Galopim de Carvalho, A. M., Santos, V. F., Povoas, L., Lopes, C., Cachão, M., Silva, C. M da & Moutinho, M. 1996. Pedreira do Galinha (Serra d'Aire), pólo de um Exomuseu da Natureza a crescer. *VII Encontro Museologia e Autarquias*, Seixal, p.16.

Garcia-Ramos, J. C., Aramburu, C.; Pinuela, L. & Ibanez, I. 2000. *La Costa de los Dinosaurios. Colunga - Ribadesella – Villaviciosa. Rutas por el Jurásico de Asturias.* Consejería de Educación y Cultura del Principado de Asturias, 33p.

Gomes, J. P. 1915-1916. Descoberta de rastos de sáurios gigantescos no Jurássico do Cabo Mondego. *Comun. Comis. Serv. Geol. Portugal*, 11: 132-134.

Kvale, E. P., Mickelson, D. L., Hasiotis, S. T. & Johnson, G. D. 2004. The History of Dinosaur Footprint Discoveries in Wyoming with Emphasis on the Bighorn Basin. *Ichnos*, 11: 3-9.

Le Loeuff, J., Gourrat, C., Landry, P., Hautier, L., Liard, R., Souillat, C., Buffetaut, E. & Enay, R. 2006. A Late Jurassic sauropod tracksite from southern Jura (France). *C. R. Palevol*, 5: 705-709.

Lockley, M. G. & Santos, V. F. 1993. A preliminary report on sauropod trackways from the Avelino Site, Sesimbra Region, Upper Jurassic, Portugal. *Gaia*, 6: 38-42.

Lockley, M. G., Meyer, C. A. & Santos, V. F. 1994. Trackway evidence of a herd of juvenil sauropods from the Late Jurassic of Portugal. *Gaia*, 10: 27-35.

Lockley, M. G., Meyer, C. A. & Santos, V. F. 1996. *Megalosauripus*, *Megalosauropus* and the Concept of Megalosaur Footprints. The Continental Jurassic, Michael Morales, ed, *Mus. Northern Arizona Bull*., 60: 113-118.

Lockley, M. G., Meyer, C. A. & Santos, V. F. 1998. *Megalosauripus* and the problematic concept of megalosaur footprints. *Gaia*, 15: 313-337.

Lockley, M. G., Mitchell, L. & Odier, G. P. 2007. Small Theropod Track Assemblages from Middle Jurassic Eolianites of Eastern Utah: Paleoecological Insights from Dune Ichnofacies in a Transgressive Sequence. *Ichnos*, 14: 131-142.

Lockley, M. G., Santos, V. F., Ramalho, M. M. & Galopim de Carvalho, A. M. 1992. Novas jazidas de pegadas de dinossáurios no Jurássico superior de Sesimbra (Portugal). *Gaia*, 5: 40-43.

Martill, D. 2000. Field Excursion to the Wealden Group (Early Cretaceous) of the Isle of Wight. *The Annual Symposium of Vertebrate Palaeontology and Comparative Anatomy.* University of Portsmouth. Available at http://www.svpca.org/years/2000_portsmouth/fieldTrip.php (cited 21.10.2008).

Mateus, O. & Antunes, M.T. 2003. A new dinosaur tracksite in the Lower Cretaceous of Portugal. *Ciências da Terra*, 15: 253-262.

Meyer, C. A., Lockley, M. G., Robinson, J. W. & Santos, V. F. 1994. A comparison of well-preserved sauropod tracks from the Late Jurassic of Portugal, and the western United States: Evidence and implications. *Gaia*, 10: 57-64.

Moratalla, J. J., Sanz, J. L. & Jiménez, S. 1997. *Dinosaurios en La Rioja. Guía de yacimientos paleoicnológicos*. Consejería de Educación, Cultura, Juventud y Deportes. Gobierno de La Rioja. Iberdrola, sección de Mineralogía y Paleontología. 175 pp.

Pavia, G. & Enay, R. 1997. Definition of the Aalenian-Bajocian Stage boundary. *Episodes*, 20 (1): 16-22.

Powell, P. 2003. Field Excursion to Ardley Quarry dinosaur trackway site and Cassington Quarry. *The Annual Symposium of Vertebrate Palaeontology and Comparative Anatomy.* Oxford University Museum of Natural History. Available at http://www.svpca.org/years/2003_oxford/fieldTrip.php (cited 21.10.2008).

Rey, J. 1983. Le Crétacé de l'Algarve: Essai de Synthèse. *Com. Serv. Geol. Portugal*, 69 (1): 87-101.

Rodrigues, L. A., Santos, V. F., Henriques, M. H., Duarte, L. V. & Galopim de Carvalho, A. M. 2002. Jurassic dinosaur tracksite of Cabo Mondego (Portugal): a geosite of the World Geological Heritage. *Journal of Vertebrate Paleontology*, 22 (3): 100A

Santos, V. F. 2003. Pistas de dinossáurio no Jurássico-Cretácico de Portugal. Considerações paleobiológicas e paleoecológicas. *Tese de Doutoramento*, Fac. Ciências da Universidade Autonoma de Madrid, 365 pp. (PhD Unpublished Dissertation).

Santos, V. F. & Rodrigues, L. A. 2003. New data on Middle Jurassic Theropods from Portugal. *51th Symp. Verteb. Palaeont. Comparative Anatomy*, Oxford. p. 39.

Santos, V. F., Galopim de Carvalho, A. M.; Brandão, J. M. 1994a. Preservação do património geológico: pistas de dinossáurios no Parque Natural das Serras d'Aire e Candeeiros. *Actas do 3º Cong. Nac. Áreas Protegidas*. Lisboa.

Santos, V. F., Galopim de Carvalho, A. M. & Silva, C. M. da 1995. A jazida da Pedreira da Ribeira do Cavalo (Sesimbra) ou a história das pegadas de dinossáurio que nunca mais poderemos visitar. *Almadam*, II Série, 4: 175-177.

Santos, V. F., Lockley, M. G., Moratalla, J. J. & Galopim de Carvalho, A. M. 1992a. The longest dinosaur trackway in the world? Interpretations of Cretaceous footprints from Carenque, near Lisbon, Portugal. *Gaia,* 5: 18-27.

Santos, V. F., Rodrigues, L. A., Cachão, M. & Galopim de Carvalho, A. M. 2001. Galinha dinosaur tracksite (Portugal). A place to learn to respect the palaeontological heritage. *6th European Workshop Vert. Paleontol.*, Florença, p. 51.

Santos, V. F., Dantas, P. M., Moratalla, J. J., Araújo, M. G. & Galopim de Carvalho, A. M. 2000a. Pegadas de terópodes em Alcanede, Portugal. *I Cong. Ibérico Paleontol./ XVI Jorn. Soc. Espanhola Paleontol.*, Évora, p. 17.

Santos, V. F., Lockley, M. G., Meyer, C. A., Carvalho, J., Galopim de Carvalho, A. M. & Moratalla, J. J. 1994b. A new sauropod tracksite from the Middle Jurassic of Portugal. *Gaia*, 10: 5-13.

Santos, V. F., Moratalla, J. J., Dantas, P. M., Cachão, M. A., Silva, C. M. da & Coke, C. J. 1992b. Pistas de dinossáurios do Cretácico superior da região de Lisboa (Portugal). Problemas de interpretação de uma pista de pegadas subcirculares. *III Cong. Geol. España y VIII Cong. Latinoamericano Geol.* Salamanca. Actas 1: 565-569.

Santos, V. F., Dantas, P. M., Moratalla, J. J., Terrinha, P., Coke, C., Agostinho, M. & Galopim de Carvalho, A. M. 2000b. Primeiros vestígios de dinossáurios na Orla Mesozóica Algarvia, Portugal. *I Cong. Ibérico Paleontol./ XVI Jorn. Soc. Espanhola Paleontol.*, Évora, pp. 20-21.

Santos, V. F., Dantas, P. M., Moratalla, J. J., Terrinha, P., Coke, C., Agostinho, M. & Galopim de Carvalho, A. M. 2000c. Rastos de Iguanodontídeos no Cretácico da Bacia Algarvia, Portugal. *I Cong. Ibérico Paleontol./ XVI Jorn. Soc. Espanhola Paleontol.*, Évora, pp. 22-23.

Santos, V. F., Moratalla, J. J., Dantas, P. M., Coke, C., Cachão, M. A., Silva, C. M. da & Sousa, L. N. 1991. Icnofósseis de Dinossáurios do Cenomaniano médio da região de Lisboa. *Actas III Cong. Nac. Geologia*, Coimbra, p. 133.

Silva, C. M. da & Cachão, M. 1998. Paleontologia Urbana: Percursos citadinos de interpretação e educação (paleo) ambiental. *Comunic. Inst. Geol. Mineiro*, 84 (2): H33-H35.

Silva, C. M. da 2007. GPS_Geologia por Satélite. Available at http://correio.fc.ul.pt/~cmsilva/Geolgps/Geolgps1.htm and http://correio.fc.ul.pt/~cmsilva/Geolgps/Geolgps2.htm (cited 15.08.2007).

Silva, C. M. da, Cachão, M., Santos, V. F., Santos, A. & Galopim de Carvalho, A. M. 1998. Património paleontológico: princípios, meios e fins. *Comunic. Inst. Geol. Mineiro*, 84 (2): G-18-G21.

New sauropod trackways from the Middle Jurassic of Portugal

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The Galinha tracksite reveals a sequence of Bajocian–Bathonian limestones belonging to the Serra de Aire Formation (West-Central Portugal) and is one of the few sites in the world where Middle Jurassic sauropod dinosaur tracks can be found. This tracksite is characterised by the presence of long, wide gauge sauropod trackways, the Middle Jurassic age of which suggests these dinosaurs were more widely distributed over time than previously thought. Two trackways contain unique pes and manus prints with morphologies that allow a new sauropod ichnotaxon to be described: *Polyonyx gomesi* igen. et isp. nov. On the basis of different manus/pes prints and trackway features, the proposal is made to subdivide Sauropodomorpha ichno-morphotypes into five groups: *Tetrasauropus*-like, *Otozoum*-like, *Breviparopus*/*Parabrontopodus*-like; *Brontopodus*-like, and *Polyonyx*-like. *Polyonyx gomesi* igen. et isp. nov. is thought to represent a non-neosauropod eusauropod, with a well developed manus digit I. The posterior orientation of this digit print suggests they were made by a eusauropod dinosaur with a posteriorly rotated pollex. The manus print morphologies observed in two trackways suggest a stage of manus structure intermediate between the primitive non-tubular sauropod manus and the tubular metacarpal arrangement characteristic of more derived sauropods. The low heteropody (manus:pes area ratio 1:2) of the trackway renders it possible they could have been made by eusauropods such as *Turiasaurus riodevensis*, which has a similar manus:pes area ratio. The *Polyonyx* igen. nov. trackway was made by non-neosauropod eusauropod, and suggests that wide gauge sauropod trackways were not exclusively made by Titanosauriformes.

Key words: Dinosauria, Sauropoda, trackways, ichno-morphotypes, Middle Jurassic, Portugal.

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Introduction

The Middle Jurassic Galinha tracksite is located on the eastern side of Serra de Aire in the municipal area of Bairro, 10 km from Fátima, within the Serra de Aire and Candeeiros Natural Park (Fig. 1). It contains very well-preserved Middle Jurassic sauropod manus and pes prints, in two of the longest sauropod trackways on record (two continuous sequences measuring 142 and 147 m). This tracksite was briefly described by Santos et al. (1994). Since then, a second Middle Jurassic tracksite has been found at Vale de Meios (Santarém), 80 km north of Lisbon. At this new site dozens of theropod trackways made by different sized trackmakers were discovered (Santos et al. 2000; Santos 2003; Santos and Rodrigues 2003), although no sauropod tracks have been identified there until recently. Santos et al. (2008) reported the existence of at least two sauropod trackways.

The sauropod trackways at the Galinha tracksite are of the wide gauge type (Santos et al. 1994: figs. 2, 3). Before this discovery was made, wide gauge sauropod trackways were not considered so widely distributed over time (Lockley et al. 1994b; Santos et al. 1994). The trackways contain exceptionally large manus prints in relation to the pes prints and, although manus claw traces have only very rarely been recorded in the literature, at the Galinha tracksite there are manus and pes prints with large claw impressions. These manus and pes prints present morphological features that distinguish them from the currently known sauropod manus and pes prints. Lockley and Meyer (2000) suggested trackways from the Galinha tracksite are distinctive enough to be recognised as a new ichnospecies. Although wide gauge sauropod trackways have been assigned to *Brontopodus* isp., those of the Galinha tracksite cannot be included in this ichnogenus due to their different manus print morphology. This paper provides a description of these sauropod tracks and a new ichnogenus and ichnospecies are formally proposed. The morphologies of the sauropod manus prints of this taxon yield information about the arrangement of the metacarpals

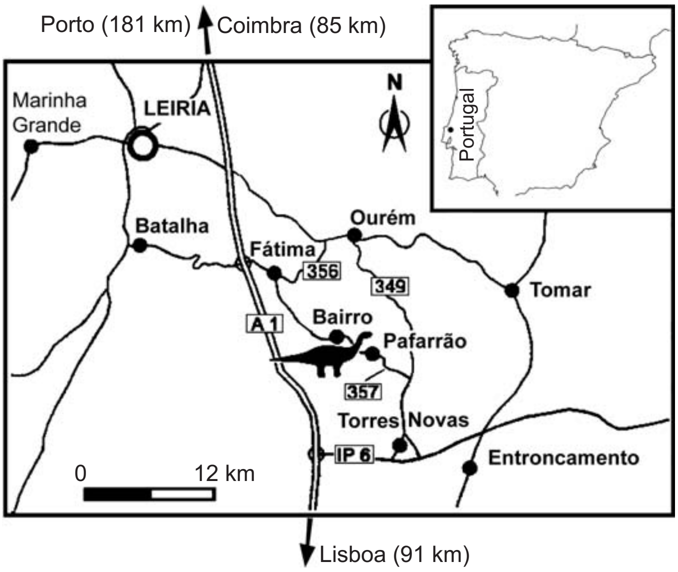

Fig. 1. Location map of the Galinha dinosaur tracksite (Bairro, Serra de Aire, West-Central Portugal). Modified from Santos et al. 1997.

and allow inferences about sauropod manus osteological structure. Further, the manus prints of the Galinha tracksite, with a long digit I appearing consistently throughout the length of two wide gauge sauropod trackways, suggest this trackway type is different from the wide gauge trackways attributed to titanosaurs; in the latter group the manus digit/claw I is absent (Salgado et al. 1997).

Institutional abbreviation.—MNDPDSA, Monumento Natural das Pegadas de Dinossáurio da Serra de Aire (Serra de Aire Dinosaur Tracks Natural Monument), Portugal.

Other abbreviations.—Dga, glenoacetabular distance; Dmp, manus-pes distance; h, hip high; λ, stride length; Pl, pes print length; Pw, pes print width; Wit and Wot, inner and outer trackway width.

Geological and stratigraphic setting

The main track level of the Galinha tracksite is a single bedding surface of about 40,000 m^2 forming the floor of an abandoned limestone quarry. A second faint trackway of probable dinosaur tracks occurs on a small, exposed surface 4 m above this level. Azerêdo et al. (1995) studied a 14 m-thick sequence of micritic limestone (Fig. 2) at the site, beginning 5.2 m below the main track level and ending at the top of the highest level observed. Based on microfacies and palaeoenvironmental studies, these authors suggested that this sequence was deposited in lacustrine, paralic and very shallow, restricted marine conditions. Some evidence from the main track level (e.g., nerineid gastropods, marine ostracods, and echinoderm fragments) suggests it was associated with shallow marine conditions (a confined, shallow, marginal marine palaeoenvironment). This palaeoenvironment developed in the innermost part of a prograding carbonate ramp, the general depositional system operating in the Lusitanian Basin at that time (Azerêdo 1993). The studied sequence of micritic limestone at the Galinha tracksite has no good stratigraphic bio-markers, however, the lithostratigraphic framework of

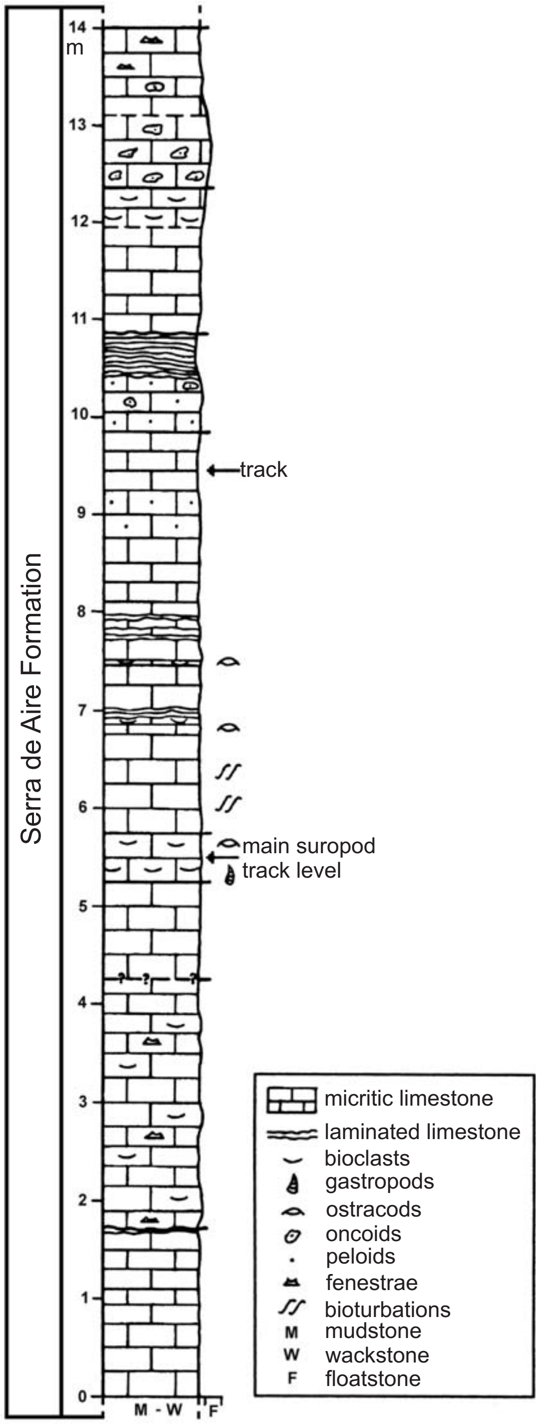

Fig. 2. Sequence of micritic limestone beginning 5 meters below the main sauropod track level of the Galinha tracksite from Serra de Aire Formation, Bajocian–Bathonian boundary (Bairro, Serra de Aire, West-Central Portugal). Modified from Azerêdo et al. (1995).

the region and its microfauna suggest that these levels belong to the Serra de Aire Formation, close to the Bajocian–Bathonian boundary (Azerêdo 1993; Azerêdo et al. 1995; Manuppella et al. 2000).

Systematic ichnology

The Galinha trackways are different from all other known sauropod trackways, and a new ichnogenus and ichnospecies are proposed based on their distinctive characteristics.

Ichnogenus *Polyonyx* nov.

Etymology: *Polyonyx* means "evidence of many claw marks" from "poly" (Greek for several) and "onyx" (Greek for claw).

Type ichnospecies: *Polyonyx gomesi* isp. nov.

Diagnosis.—As for the type, and only known ichnospecies.

Polyonyx gomesi isp. nov.

Figs. 3–5.

Etymology: In memory of Jacinto Pedro Gomes (1844–1916), curator of the Museu Mineralógico e Geológico da Escola Politécnica (Lisbon, Portugal), the first naturalist to study (in 1884) dinosaur tracks in Portugal (Gomes 1916).

Holotype: A trackway in situ (142 m long with 94 consecutive manus-pes print sets; reference G5) at the Galinha tracksite classified as a Natural Monument—Monumento Natural das Pegadas de Dinossáurio da Serra de Aire (Serra de Aire Dinosaur Tracks Natural Monument), Portugal. In MNDPDSA centre there is a cast with a sequence of a left manus print, two pairs of manus-pes prints and a right pes print (reference MNDPDSA-G5).

Type horizon: Serra de Aire Formation, close to the Bajocian–Bathonian boundary, Middle Jurassic (Azerêdo 1993; Azerêdo et al. 1995).

Type locality: Galinha tracksite, Municipal area of Bairro, Serra de Aire, West-Central Portugal.

Diagnosis.—Wide gauge sauropod trackway revealing low heteropody (manus-pes area ratio 1:2) and two autapomorphies: (1) asymmetric manus prints with large digit I marks oriented in a medial direction with a large, posteriorly oriented, triangular claw mark, and impressions of digits II, III, IV and V; (2) pes prints with four claw marks: claws I–II with an anterior orientation, and III–IV laterally oriented. Manus digits II–V show a slightly bent arrangement.

Description.—This trackway is a wide gauge sauropod trackway with an inner trackway width 1.2 times the footprint width (Wit/Pw; see Tables 1 and 2, Fig. 5). The manus prints are wider than long with a rounded lateral edge (digit mark V), a large digit I mark oriented in a medial direction and with a large, posteriorly oriented, triangular claw mark I, and impressions of digits II–IV (Fig. 4A). Other manus prints of trackway G5 show digit II–IV marks at the anterior margin. The pes prints are longer than wide, oval shaped, and have four claw marks (claws I–II with an anterior orientation, and III–IV laterally oriented). The ichnospecies shows low heteropody (the pes area is about twice the manus print area). Occasionally, the manus print centres are closer to the trackway midline than the pes print centres. Both the manus and pes prints are rotated outward relative to the trackway midline. Considering the direction of the manus and pes print width in relation to trackway midline, the rotation values for the manus prints are vary from 25° to 50° and the pes print values from 25° to 42°. With respect to the pes print length, the outer trackway width is 2.7 times wider (Wot/Pl, Table 2), the manus-pes distance is 0.3–0.6 times longer (Dmp/Pl, Table 2), and the stride length is 3.4 times longer (λ/Pl, Table 2). The glenoacetabular distance is three times the pes print length (Dga/Pl, Table 2) and 1.1 times the outer trackway width (Dga/Wot, Table 2). The pace angulation value is about 95°.

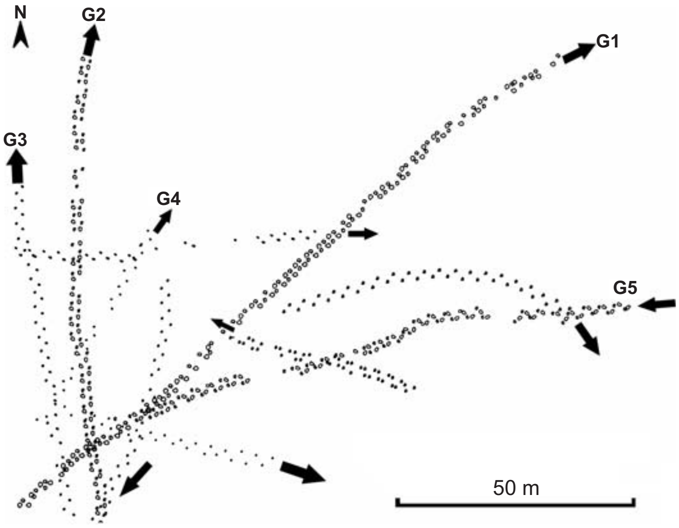

Fig. 3. Long sauropod trackways at the Galinha dinosaur tracksite (Bairro, Serra de Aire, West-Central Portugal). Trackway G1 is 147 m long and trackway G5 is 142 m long. Modified from Santos (2003).

Stratigraphic and geographic range.—Bajocian-Bathonian of West-Central Portugal.

Polyonyx isp.

Figs. 6, 7.

Material.—One trackway (147 m long) with 97 consecutive manus-pes print sets (reference G1).

Stratigraphic and geographic range.—As for the type ichnospecies.

Description of the Galinha trackways

At least 20 sauropod trackways, including several that show excellent preservation of both the manus and pes prints, and others that are manus-only sequences, are present at level 1 of the Galinha tracksite. The ten best-preserved trackways were studied and illustrated (Fig. 3) and individual tracks traced using transparent acetate overlays (Santos 2003). The space between the pes print medial margins shows them all to be wide gauge trackways.

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Table 1. Characteristic values of sauropod tracks and trackways of Galinha tracksite (Bairro, Serra de Aire, West-Central Portugal). L, length; W, width; h, hip high; λ, stride length; Dga, glenoacetabular distance; Wot, Wit, outer and inner trackway width; Dmp, manus-pes distance. All values in centimetres. (*), obtained through manus prints; (**), estimated value.

Trackway	L × W		h	λ	λ/h	Dga	Wot	Wit	Dmp	Trackmaker speed (km/h)
	PES	MANUS								
G-1	95 × 70	40 × 75	380	315	0.8	300	215	60	56	4.0
G-2	80 × 65	42 × 60	320	320	1.0	270	180	40	40	5.1
G-3	–	27 × 45	–	300*	–	–	180	90**	–	–
G-4	–	20 × 34	–	380*	–	–	150	70**	–	–
G-5	90 × 60	38 × 58	360	310	0.9	270	240	70	25–50	4.1

Table 2. Characteristic values of sauropod tracks and trackways at Galinha tracksite (Bairro, Serra de Aire, West-Central Portugal) and *Brontopodus birdi* (modified from Farlow et al. 1989). Wot and Wit, outer and inner trackway width; Pl and Pw, pes print length; pes print width; Dmp, manus-pes distance; λ, stride length; Dga, glenoacetabular distance.

Trackway	Wot/Pl	Wit/Pw	Dmp/Pl	λ/Pl	Dga/Pl	Dga/Wot
Brontopodus birdi	1–1.5	0.8	0.5–1.2	2–5	3–4	1.3
G-1	2.3	0.9	0.6	3.3	3.2	1.4
G-2	2.2	0.6	0.5	4.0	3.3	1.5
G-5	2.7	1.2	0.3–0.6	3.4	3.0	1.1

Trackway G1: *Polyonyx* isp.—Trackway G1 is a 147 m long wide gauge sauropod trackway (Fig. 6) with 97 consecutive manus-pes sets with an inner trackway width of about 60 cm (Fig. 6A, Table 1). G1 contains oval pes prints and crescent shaped manus prints, sometimes overlapping but in general with a manus-pes distance of 56 cm (Table 1). The ratio of manus-pes distance/pes print length is 0.6 (Table 2). Both the manus and pes prints are rotated strongly outward relative to the trackway midline. The outward rotation values for the manus prints vary from 50° to 58°; the values for the pes prints vary between 23° and 35°. Bonnan (2003: 607) refers to a "supination" angle of about 55° for these manus prints and considered them to be "the most supinated tracks yet reported". Sometimes, the manus print centres are closer to the trackway midline than the pes print (Fig. 6A). The manus prints are wider than long (40 cm long by 75 cm wide, Table 1) and have a slightly bent metacarpal arch. They have rounded lateral and medial margins and a long and narrow impression (20 cm long by 6 cm wide) projecting from the centre of the track's rear margin and oriented in a posteromedial direction (Fig. 6B). The well-preserved oval-shaped pes prints which have no claw marks (Figs. 6A, 7) are longer than wide—95 cm long by 70 cm wide (Table 1). In general, both the manus and pes prints are 2 cm deep, surrounded by a rim (Fig. 7). The best-preserved pes impressions show two depressed areas separated by a rim perpendicular to the long axis of the pes (Figs. 6A, 7). This rim represents an anterior area where the foot pressed the ground at the last moment of the step cycle. The pes area is about twice the manus print area, and the pace angulation is about 113°.

Tables 1 and 2 provide the stride length and other characteristic values of the trackways and trackmakers. With respect to the pes print length (Pl), the stride length is 3.3 times longer and the glenoacetabular length is 3.2 times longer (λ/Pl and Dga/Pl, Table 2). The glenoacetabular distance is 1.4 times the outer trackway width (Dga/Wot, Table 2). The outer trackway width is 2.3 times the pes print length, and the inner trackway width is 0.9 times the pes print width (Wot/Pl and Wit/Pw, Table 2).

Trackway G2: no ichnotaxonomic assignment.—Trackway G2 is a 110 m-long wide gauge sauropod trackway with an inner trackway width of about 40 cm (Table 1), showing oval pes prints and crescent-shaped manus prints rotated outwards relative to the trackway midline (Fig. 3). The mean manus-pes distance is about 40 cm (Table 1) but sometimes the pes prints overlap the manus prints. The manus-pes distance/pes print length ratio is 0.5 (Dmp/Pl, Table 2). The manus prints are crescent shaped and wider than long (42 cm long by 60 cm wide, Table 1) with a slightly bent metacarpal arch. The oval shaped pes prints, none of which have claw marks, are longer than broad (80 cm long by 65 cm wide, Table 1). The manus:pes area ratio is 1:2 (low heteropody) and the pace angulation is about 112°.

With respect to the pes print length (Pl), the stride length is four times longer and the glenoacetabular length 3.3 times longer (λ/Pl and Dga/Pl, Table 2). The glenoacetabular distance is 1.5 times the outer trackway width (Dga/Wot, Table 2). The outer trackway width is 2.2 times the pes print length, and the inner trackway width is 0.6 times the pes print width (Wot/Pl and Wit/Pw, Table 2).

Trackways G3, G4: no ichnotaxonomic assignment.—Several wide gauge trackways are formed either by crescent-shaped manus impressions alone (Fig. 3) or dominated by manus prints (e.g., trackways G3 and G4, Table 1) with faint traces of pes toe impressions (Santos et al. 1994).

Trackway G5: *Polyonyx gomesi* holotype.—Trackway G5 is a sauropod trackway with 94 consecutive manus-pes sets extending over a distance of 142 m (Figs. 3, 5). It shows oval

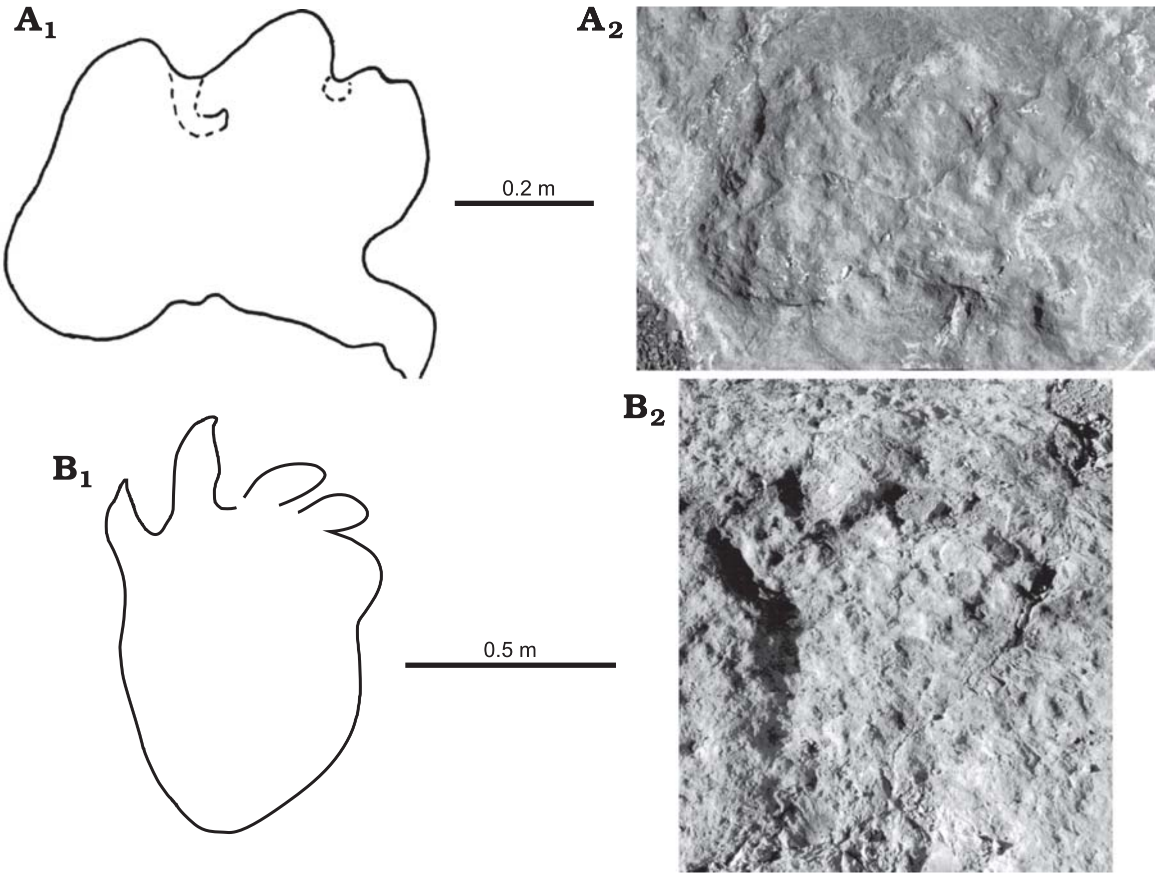

Fig. 4. *Polyonyx gomesi* igen. et isp. nov., sauropod manus and pes prints from trackway G5 at the Galinha dinosaur tracksite (Bairro, Serra de Aire, West-Central Portugal). **A**. Outline (A_1) and photograph (A_2) of a left manus print. **B**. Outline (B_1) and photograph (B_2) of a right pes print. Modified from Santos (2003).

pes prints and crescent shaped manus prints. The inner trackway width (Wit) is about 70 cm (Table 1). Sometimes the pes prints overlap the manus prints, but in general the manus-pes distance ranges from 25 to 50 cm (Table 1). The manus-pes distance/pes print length ratio is 0.3–0.6 (Dmp/Pl; Table 2). Both the manus and pes prints are outwardly rotated relative to the trackway midline. The outward rotation values for the manus prints vary from 25° to 50°; values for the pes prints are 25–42°. Sometimes the manus print centres are closer to the trackway midline than the pes print centres (Fig. 5). The manus prints are wider than long (38 cm long by 58 cm wide, Table 1) and are asymmetrical with a large digit I impression oriented in a medial direction, a large, posteriorly oriented, triangular claw I mark, and impressions of digits II–V with a slightly bent arrangement (Fig. 4A). Therefore, the manus impressions reveal a large claw I mark as well as impressions of digits II–V arranged in a slightly bent metacarpal arch. The well-preserved pes prints are longer than broad and oval shaped (90 cm long by 60 cm wide, Table 1), and show four claw marks: claws I and II show an anterior orientation and claws III and IV are laterally oriented (Fig. 4B). The best-preserved manus and pes prints are 2 cm deep and show a mud rim. Low heteropody (the manus:pes area ratio is 1:2) is another distinctive feature. The pace angulation is about 95°. Tables 1 and 2 show the stride lengths and other values of the G5 tracks and trackway. In relation to the pes print length, the stride length is 3.4 times longer and the glenoacetabular distance is 3 times longer (λ/Pl and Dga/Pl, Table 2). The estimated glenoacetabular distance is 1.1 times the outer trackway width (Dga/Wot, Table 2). The outer trackway width is 2.7 times the pes print length, and the inner trackway width is 1.2 times the pes print width (Wot/Pl and Wit/Pw, Table 2).

Comparison of the Galinha trackways with the general sauropod track record

Sauropod trackways from Galinha tracksite were compared with tracks from different places and ages. Few Lower Jurassic sauropod trackways are known. Narrow-gauge trackways similar to *Parabrontopodus* isp. with relatively small pes prints were reported by Gierliński (1997) from central Poland and by Leonardi and Mietto (2000) from Lavini di Marco (Italy). However, these trackways are clearly distinct from the much larger Portuguese Middle Jurassic wide gauge sauropod trackways, showing a smaller inner trackway width, high

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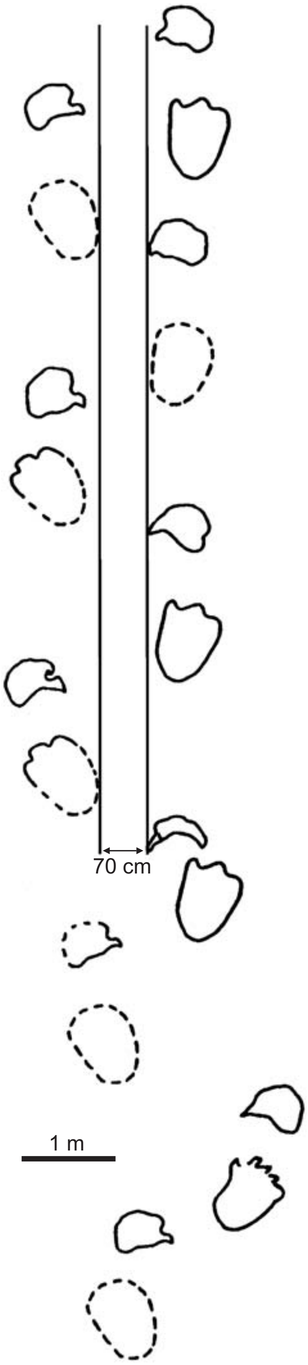

Fig. 5. Segment of G5 sauropod trackway at the Galinha dinosaur tracksite (Bairro, Serra de Aire, West-Central Portugal): *Polyonyx gomesi* igen. et isp. nov. Modified from Santos (2003).

heteropody, and crescent-shaped manus prints without digit/claw marks.

The Middle Jurassic sauropod track record is also poorly known. Narrow- and wide gauge sauropod trackways have been reported from the Middle Jurassic of Morocco (Dutuit and Ouazzou 1980; Ishigaki 1988, 1989); these authors report unnamed wide gauge trackways showing footprints with four digit impressions and manus prints with no digit marks. They also report narrow-gauge trackways such as *Parabrontopodus* isp. These Moroccan manus and pes print morphologies (Fig. 8H, J), and the size of the manus related to the pes prints, are different from the Portuguese Middle Jurassic sauropod track record (Fig. 8A, B, K). *Breviparopus taghbaloutensis* Dutuit and Ouazzou, 1980 from the Middle Jurassic of Morocco is represented by narrow-gauge sauropod trackway with anteriorly oriented pes claw marks (Fig. 8J), crescent-shaped manus prints without digit marks, and high heteropody (Ishigaki 1989). The inner trackway width, pes claw mark orientation and manus print shape of *B. taghbaloutensis* are similar to those of *Parabrontopodus* isp.

Romano et al. (1999) reported sauropod prints from the Middle Jurassic of Yorkshire, England. Some of the oval pes prints described show digit prints rotated outwards relative to the trackway midline that resemble those of *Brontopodus*. The manus prints are crescent-shaped with no digit impressions. These British prints differ from the Portuguese prints in manus and pes morphology and heteropody (Romano and Whyte 2003: 201). These have been reinterpreted as stegosaur tracks by Whyte and Romano (2001).

Day et al. (2002) reported long sauropod trackways from the Middle Jurassic of Oxford, England. Some of these trackways are wide gauge (Day et al. 2002, VFS, personal observation 2003) and are similar to the Portuguese trackways, but they do not show such low heteropody. Further, the manus prints show no digit/claw marks. Narrow-gauge trackways, very similar to *Parabrontopodus* isp., were also reported from the Oxford tracksite. However, these are quite different from the wide gauge sauropod trackways at the Galinha site.

Upper Jurassic sauropod trackways have been found at seven tracksites in Portugal but only two trackways reveal claw traces. At Lagosteiros Bay (Cabo Espichel) there are wide gauge trackways that show pes prints with four laterally rotated claw marks (Fig. 8M) and small crescent shaped manus prints without digit impressions (Meyer et al. 1994). These tracks were attributed to *Brontopodus* isp. (Meyer et al. 1994) based on their inner trackway width, their manus and pes print morphologies, and heteropody. However, they differ from trackways G1 and G5 at the Galinha tracksite with respect to their heteropody and manus/pes print morphologies (Fig. 8). A quadrupedal trackway with one very slight pes impression and seven crescent shaped manus prints with five prominent claw marks has been described for the Upper Jurassic of the Sesimbra region (Santos et al. 1995; Santos 2003). In this trackway, the manus claw I mark shows a medial orientation (Fig. 8C). The manus print morphology is quite different to all other known sauropod manus print morphologies (Fig. 8).

Lires (2000) reported narrow and wide gauge sauropod trackways from the Upper Jurassic of Asturias (northern Spain) and recognised three different pes print morphotypes. One of these is similar to *Brontopodus* isp. pes prints (Fig. 8N) and therefore, different to the pes prints of trackways G1 and G5 at the Galinha tracksite. *Gigantosauropous asturiensis* from the Late Jurassic of Spain (Mensink and Mertmann 1984; Lockley et al. 1994a, 2007) is represented by a narrow-gauge trackway. However, there are no morphological

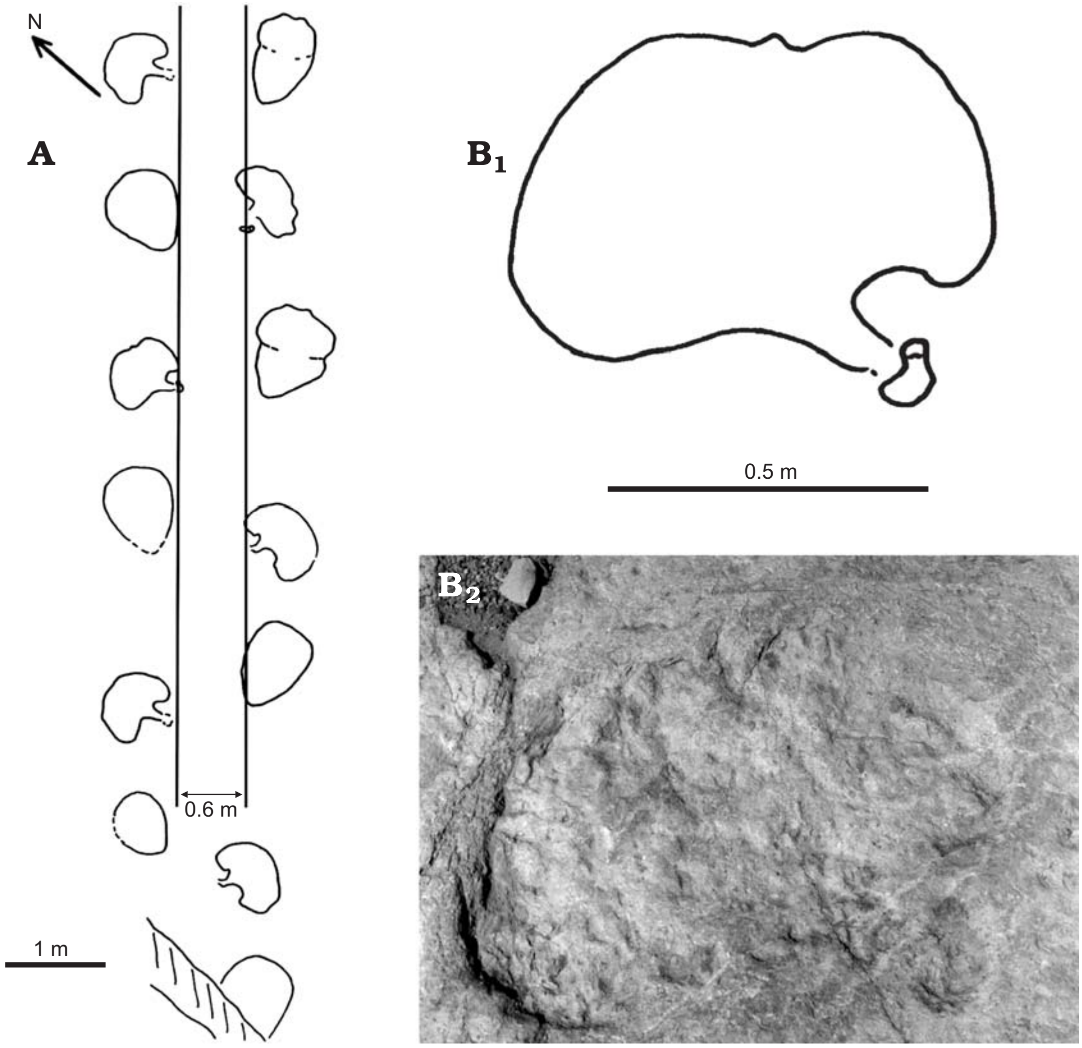

Fig. 6. *Polyonyx* isp., sauropod trackway G1 at the Galinha dinosaur tracksite (Bairro, Serra de Aire, West-Central Portugal). **A**. Trackway segment. **B**. Outline (B_1) and photograph (B_2) of left manus print with a slender and long impression in the centre of the track's rear margin oriented in a postero-medial direction. Modified from Santos (2003).

features that could allow a comparison with the sauropod trackways at the Galinha tracksite.

Lower Cretaceous sauropod trackways are also quite different from the Portuguese Middle Jurassic sauropod trackways at the Galinha tracksite in terms of their manus and pes print morphologies. Dalla Vecchia (1999) reported a manus print from the Upper Hauterivian–Lower Barremian of north-eastern Italy, showing a relatively well developed claw on digit I (Fig. 8D). This manus print reminds one of *Brontopodus birdi* Farlow, Pittman, and Hawthorne, 1989 manus print morphology. *Titanosaurimanus nana* Dalla Vecchia and Tarlao, 2000 from the Lower Cretaceous of Croatia shows small size U-shape manus prints with distinctive digit impressions (Fig. 8E), quite different from the manus print morphologies observed at the Galinha tracksite (Fig. 8A, B).

The Middle Jurassic sauropod trackways at the Galinha tracksite are clearly wide gauge with inner trackway width values even greater than those of *B. birdi* from the Lower Cretaceous of the USA (Table 2). Trackway G2 from the Galinha tracksite is not comparable to *B. birdi* in terms of manus and pes print morphologies. On the contrary, the general G2 manus print morphology is more similar to that of the G1 manus tracks than that of *Brontopodus*. Trackways G3 and G4 are manus-dominated, showing crescent shaped morphology (Fig. 3; Santos et al. 1994: fig. 5; Lockley and Meyer 2000: fig. 6.6.). Their arrangement suggests they are part of a wide gauge trackway. Despite the absence of digit marks, the morphology of the G3 and G4 manus prints seems to be more similar to the G1 manus prints than those of *Brontopodus*. Trackways G1 and G5 are distinct from *B. birdi* in terms of their heteropody and manus and pes print morphologies (Fig. 8). Shape analysis (using geometric morphometric techniques) performed on 30 sauropodomorph pes prints from the ichnological world record (Rodrigues and Santos 2004) corroborates the inference that the G5 trackway pes print morphology is clearly different from that of *Brontopodus* pes prints. Indeed, *B. birdi* pes prints show all their digit marks laterally oriented, with a small digit IV claw

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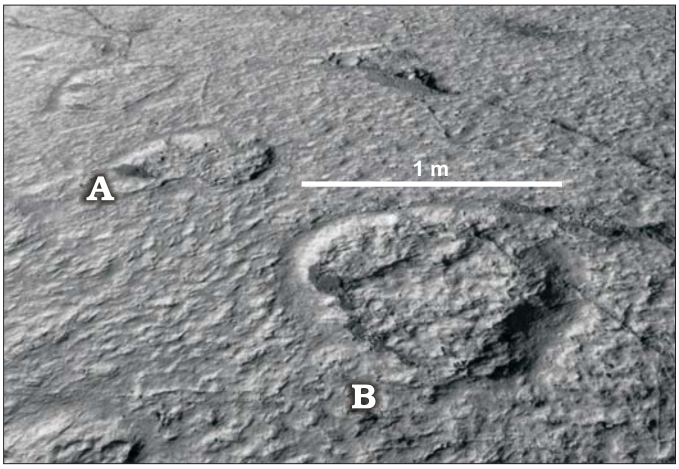

Fig. 7. *Polyonyx* isp., sauropod trackway G1 at the Galinha dinosaur tracksite (Bairro, Serra de Aire, West-Central Portugal). **A**. Sauropod right manus. **B**. Sauropod right pes prints. Photograph by Carlos Marques da Silva.

mark and a small digit V mark callosity, while along the G5 trackway at least ten pes prints reveal claw marks I and II to have an anterior orientation, and claw marks III and IV to be laterally oriented. Moreover, *Brontopodus birdi* pes prints have digit print IV situated in a more posterior position than in the G5 trackway pes prints. The Portuguese Middle Jurassic sauropod manus prints, with their slightly bent metacarpal arch, also show different morphology to *B. birdi* manus prints. In *B. birdi* these prints are U-shaped, reflecting an osteological tubular structure, and show clear evidence of rounded marks made by digits I and V in a more posterior position (Fig. 8F). Digits II–IV seem to be arranged together and their impressions are crescent-shaped. *Rotundichnus* is represented by a not particularly well-preserved wide gauge sauropod trackway from the Lower Cretaceous of Germany (Hendricks 1981). This is considered a *Brontopodus*-like trackway (Lockley et al. 2004). A Lower Cretaceous sauropod trackway with circular tracks from Argentina—*Sauropodichnus giganteus*—(Calvo 1991) is so poorly preserved that they cannot be used in any comparison with the Galinha trackways.

Sauropod tracks known from the Early Cretaceous of Korea were assigned to cf. *Brontopodus* (e.g., Lim et al. 1994; Huh et al. 2003; Lockley et al. 2008). Therefore, Korean sauropod tracks are clearly distinct, as the Portuguese Middle Jurassic sauropod tracks differ from those assigned to *Brontopodus*.

The Upper Cretaceous sauropod track record also yields U-shaped manus prints. Lockley et al. (2002) described several sauropod trackways from the Upper Cretaceous of Bolivia at the Humaca site. In these trackways the manus prints are semicircular with five rounded callosities or blunt claw impressions (Fig. 8G). The pes prints are sub-triangular and sometimes show three blunt, equidimensional claw impressions belonging to digits I–III (Lockley et al. 2002: 392). The morphology of these manus prints is different from those of the Portuguese Middle Jurassic sauropod manus prints (Fig. 8A, B). It is interesting to note that one trackway at the Toro Toro site (Leonardi 1994: 193) is wide gauge and its heteropody even lower than that of the Portuguese Middle Jurassic sauropod trackways. The Humaca site shows sauropod trackways with relatively high heteropody (Lockley et al. 2002: fig. 7) and others with low heteropody (Lockley et al. 2002: fig. 9). The trackways are narrow-gauge with inner trackway widths of about 0–15 cm, quite different from the Portuguese Middle Jurassic wide gauge trackways.

The wide gauge sauropod trackways of the Fumanya tracksite (SE Pyrenees) were described by Schulp and Brokx (1999) and later by Vila et al. (2005). These lower Maastrichtian tracks (Oms et al. 2007) show subrounded manus prints with a U-shaped morphology. They are quite similar to

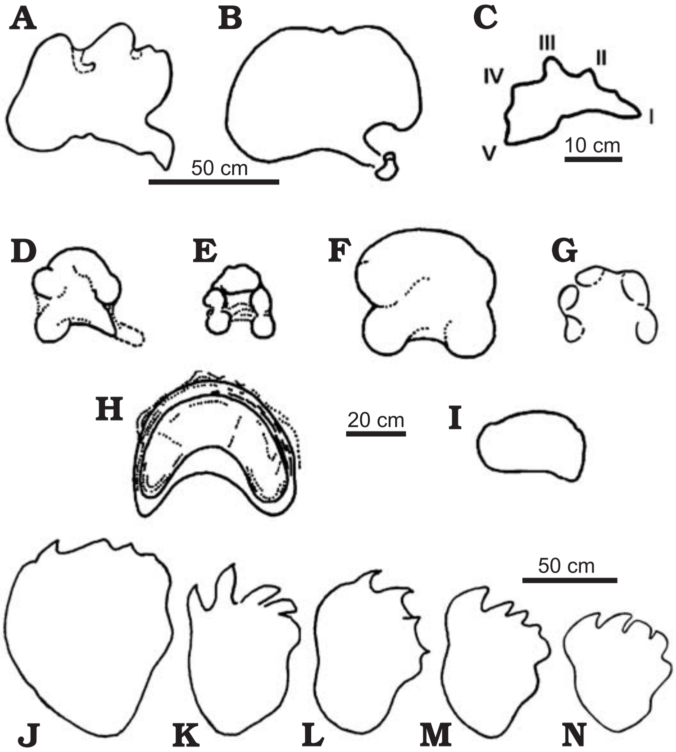

Fig. 8. Sauropod ichnites with well preserved morphologies from the general track record. **A**–**I**. sauropod manus prints (redrawn from Dalla Vecchia and Tarlao 2000). **A**. *Polyonyx gomesi* igen. et isp. nov. from the Middle Jurassic of Portugal. **B**. *Polyonyx* isp. from the Middle Jurassic of Portugal. **C**. left manus print of a quadrupedal dinosaur from the Upper Jurassic of Portugal. **D**. Unnamed print from the Lower Cretaceous of Italy. **E**. *Titanosaurimanus nana* from the Early Cretaceous of Croatia. **F**. *Brontopodus birdi* from the Lower Cretaceous of USA. **G**. Unnamed print from the Upper Cretaceous of Bolivia. **H**. *Breviparopus taghbaloutensis* from the Middle Jurassic of Morocco. **I**. *Parabrontopodus mcintoshi* from the Upper Jurassic of USA. **J**–**N**. Sauropod pes prints. **J**. *Breviparopus taghbaloutensis* from the Middle Jurassic of Morocco. **K**. *Polyonyx gomesi* igen. et isp. nov. from the Middle Jurassic of Portugal. **L**. *Brontopodus birdi* from the Lower Cretaceous of USA. **M**. *Brontopodus* aff. *B. birdi* from the Upper Jurassic of Portugal. **N**. Unnamed print from the Upper Jurassic of Asturias, Spain. A, B, K, after Santos et al. (1994); C, after Santos et al. (1995), Santos (2003); D, after Dalla Vecchia 1999; E, after Dalla Vecchia and Tarlao 2000; F, L, after Farlow at al. (1989); G, after Lockley et al. (2002); H, J, after Dutuit and Ouazzou (1980), Ishigaki (1989); I, after Lockley et al. 1994a; M, after Meyer et al. 1994, Santos 2003; N, after Lires 2000.

the characteristic *Brontopodus* isp. manus prints and therefore clearly distinct from the Portuguese Middle Jurassic sauropod tracks characterised by low heteropody and different manus print morphologies.

Dalla Vecchia (1999) and Dalla Vecchia and Tarlao (2000) analysed the world sauropod track record and suggested three sauropod manus morphotypes based on the configuration of digit I: Morphotype A, which comprises manus prints with a well-developed impression of the digit I claw (these authors considered trackway G5 from Galinha tracksite to belong to this morphotype); Morphotype B, characterised by manus prints with the intermediate development of a digit I claw (these authors considered trackway G1 from Galinha tracksite to belong to this morphotype); and morphotype C with manus prints without a claw I mark, and with rounded marks made by digits I and V (*Brontopodus* isp).

Discussion

There has been a long debate about why the claw I print is not normally preserved in sauropod manus prints (e.g., Ginsburg et al. 1966; Farlow et al. 1989), and in at least one paper it has been suggested that sauropods walked on their knuckles with their digits rotated backwards (Beaumont and Demathieu 1980). However, osteological studies revealed that the sauropod metacarpus was held fully erect with the metacarpals forming a semicircle in dorsal view; this is confirmed by the crescent shape of sauropod manus prints (see e.g., Farlow et al. 1989; McIntosh 1990; Meyer et al. 1994; Moratalla et al. 1994; Santos et al. 1994; Christiansen 1997).

Consequently, the osteological record and the ichnological evidence suggest that sauropods did not walk on their knuckles (Christiansen 1997). The Galinha tracksite shows the best preserved impressions of any sauropod manus digit I known to date.

Farlow (1992) was the first to recognise and define narrow and wide gauge sauropod trackways. Lockley et al. (1994a) proposed *Brontopodus birdi* (Farlow et al. 1989) to represent a wide gauge sauropod trackway and *Parabrontopodus* isp. (Lockley et al. 1986) as an example of narrow-gauge sauropod trackway (those with no space between the inner footprint margins). The inner trackway width of trackway G1 from the Galinha tracksite clearly renders it a wide gauge trackway, just like trackway G5 and *Brontopodus birdi* (Wit, Table 1; Wit/Pw, Table 2). This fact undoubtedly establishes the presence of wide gauge sauropod trackway makers in the Middle Jurassic of Portugal (Santos et al. 1994). Galinha trackways have manus and pes prints with morphological features totally different from *Brontopodus* isp. manus and pes prints and do not obviously suggest their inclusion in this ichnotaxon. The most interesting and distinctive feature of trackway G1 is the long and narrow impression at the centre of the manus track's rear margin, oriented in a posterior-medial direction. This mark can be observed with the same morphology and occupying the same position in both left and right manus prints along the trackway (Fig. 6). This consistency over the same trackway rules out the possibility of this impression being an extramorphological artefact. If taphonomic or preservational alterations were solely responsible for the peculiar morphology of this impression, it would not be reasonable to expect such a regular record of this impression along the trackway. It is also too long and slender to be a metacarpus impression. Moreover, the anatomical position of the sauropod metacarpus suggests that it did not touch the ground. The most posterior region of this slender impression seems to be the distal trace of a claw.

Trackway G5 shows manus prints with a large mark oriented in a medial direction, with the same morphology and occupying the same position in both left and right manus prints along the trackway (Figs. 4, 5). These regular and repeated manus print morphologies observed in the G1 and G5 trackways reflect the biological structure of the trackmaker's forefeet. Therefore, the following are here interpreted as a manus digit I mark: (i) the impression at the centre of the manus print's rear margin, oriented in a posterior-medial direction, in trackway G1; and (ii) the large impression oriented in a medial direction with a sharp, posteriorly oriented mark, in trackway G5. The posterior position of manus digit I impressions suggests that metacarpus I also occupies a posterior position, and consequently that the whole metacarpus was built as a semitubular structure. The morphology of the trackway G5 manus prints shows similarities and differences to the trackway G1 manus prints. The similarities are the slightly bent metacarpal arch and the low heteropody (manus:pes area ratio 1:2). However, the trackway G5 manus prints show five digit impressions, while the trackway G1 manus prints show only the digit I print. Also, the shape and the orientation of digit I in the manus prints are different: both originate at the centre of the track's concave posterior margin, but in trackway G5 digit I is slightly more medially positioned with an acuminated, posteriorly oriented distal end (Fig. 4). Finally, the trackway G5 pes prints show four conspicuous digit marks not seen in trackway G1 pes prints (Figs. 4, 6). Some of these morphological differences could be a result of preservation but others probably reflect anatomical structures. Despite these morphological differences between G1 and G5 trackways it is still uncertain which features are diagnostic at the ichnospecies level. For this reason the G1 trackway is attributed to *Polyonyx* isp.

According to Wilson and Sereno (1998), the pes ungual phalanges of sauropods are oriented in an external direction (as seen in the footprints illustrated in Fig. 8K–N), but this is not evident in *Polyonyx gomesi* igen. et isp. nov. The pes print digits I and II show an anterior orientation while digits III and IV have a lateral orientation (Fig. 8K). It is interesting to note that *Breviparopus taghbaloutensis* (Fig. 8J) pes prints also show anteriorly (or slightly laterally) directed digit claw marks.

Brontopodus birdi manus prints are also quite different from the sauropod manus prints at the Galinha tracksite. The former manus prints are U-shaped (suggesting all the metacarpals are arranged regularly) and show rounded marks of digits I and V almost side by side at the posterior margin.

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Table 3. Sauropodomorpha ichno-morphotypes based on trackway features and pes and manus prints morphotypes (after Dalla Vecchia 1999; Dalla Vecchia and Tarlao 2000; Avanzini et al. 2003; D'Orazi Porchetti and Nicósia 2007).

Sauropodomorpha ichno-morphotypes	Main prints and trackways characteristics
Tetrasauropus-like	1. Narrow gauge trackways. 2. Elongated and tetradactyl pes prints with four inward arched and clawed digits, a well developed digit IV along the lateral margin of the foot and a very short digit I in medial margin. 3. Small manus prints with four inward arched claw marks. 4. High heteropody.
Otozoum-like	1. Trackmaker generally bipede and quadrupede. 2. Narrow-gauge trackway. 3. Elongated pes prints with four inward digit marks, a well-developed mark of digit IV along the lateral margin of the footprint. 4. High heteropody.
Breviparopus-like/ *Parabrontopodus*-like	1. Narrow-gauge trackway. 2. Wide pes prints with anteriorly (or slightly outwardly) directed claw or digit marks. 3. Crescent shaped manus prints. 4. High heteropody.
Brontopodus-like	1. Wide-gauge trackway. 2. Pes prints longer than broad, with large, outwardly directed claw marks at digits I–III, a small claw at digit IV and small callosity or pad mark at digit V. 3. U-shaped manus prints with rounded marks of digits I and V. 4. High heteropody.
Polyonyx-like	1. Wide-gauge trackway. 2. Pes prints with four claw marks (claws I–II oriented in an anterior direction; claws III–IV oriented laterally). 3. Asymmetric manus prints with large digit I mark oriented in a medial direction and a large triangular claw mark I posteriorly oriented, and impressions of digits II–V. Slightly bent disposition of manus digits II–III–IV and V. 4. Low heteropody.

This metacarpal arrangement suggests a tubular structure for *B. birdi* trackmaker manus. On the contrary, the sauropod manus prints at the Galinha tracksite suggest an incompletely tubular metacarpal arrangement; they are not arranged in such a regular pattern. Metacarpals II–V are slightly bent while metacarpal I is positioned in a more posterior position. It is therefore suggested that the sauropod manus morphologies preserved at the Galinha tracksite are the consequence of a semi-tubular metacarpal structure not yet reported. This arrangement would represent a functional tubular structure but with a more primitive metacarpal (semi-tubular) arrangement.

Several authors believe the sauropod manus probably functioned as a single, rigid, block-like structure with no intermetacarpal movements (McIntosh 1990; Upchurch 1994; Bonnan 2003). Movement of the phalanges of digits II–IV appear to have been restricted (e.g., Christiansen 1997) while a pollex claw, present in many sauropods, may have possessed a limited range of flexion and extension (see e.g., Thulborn 1990; Upchurch 1994). Thus, the sauropod manus appears to have functioned as a rigid structure to support the body weight, and had a claw I with some degree of movement. The semi-tubular arrangement of the metacarpus of the G1 and G5 trackmakers, plus the posterior-medial pollex orientation, suggest that this digit may have been capable of some independent movement. However, the orientation, length and general appearance of the digit I print is very constant over the trackway, suggesting that, at least during locomotion, its orientation was relatively fixed. It should be mentioned that the posterior-medial orientation of the manus digit I prints in the trackways suggests the presence of an unknown eusauropod with the pollex posteriorly rotated. The relatively large size of the manus and the semi-tubular arrangement of the metacarpus may have improved the support capability of the trackmaker manus during locomotion.

On the basis of different manus/pes prints and trackway features known in the track record Avanzini et al. (2003) suggested that Sauropodomorpha ichno-morphotypes could be subdivided into four main groups based on their pes print morphology: *Tetrasauropus*-like (sensu *Tetrasauropus* Ellenberger 1972), *Otozoum*-like, *Breviparopus*-like, and *Brontopodus*-like. Recently *Tetrasauropus* was amended and defined by D'Orazi Porchetti and Nicósia (2007) but it is still considered an ichnotaxon related to sauropodomorphs. Lockley et al. (2006) distinguish tracks from North America previously referred to *Tetrasauropus* from *Evazoum* (Nicosia and Loi 2003). *Tetrasauropus* is an ichnotaxa reserved to large-sized quadrupedal tracks with a tetradactyl pes showing a strong ectaxony, with the foot axis almost parallel to the midline of the trackway, strong claws which in the pes bend inward and the manus smaller than the pes (about 2/3) with four digits (D'Orazi Porchetti and Nicósia 2007). In addition to the proposal suggested by Avanzini et al. (2003) to subdivide Sauropodomorpha ichno-morphotypes into four groups we suggest that a fifth subdivision exists due to the manus/pes prints and trackway features of the ichnotaxon herein proposed: *Tetrasauropus*-like (sensu Ellenberger 1972; emended by D'Orazi Porchetti and Nicósia 2007), *Otozoum*-like, *Breviparopus*/ *Parabrontopodus*-like; *Brontopodus*-like, and *Polyonyx*-like (Table 3).

Middle Jurassic sauropod trackmakers

Lockley et al. (1994a) suggested brachiosaurids as trackmakers of classic wide gauge sauropod trackways and later they have been assigned to Titanosauriformes according to the phylogenetic proposal of Wilson and Carrano (1999). However, the features of the wide gauge sauropod trackways at the Galinha tracksite, with a large manus claw I mark and manus prints with a slightly bent metacarpal arch, do not support such an assignation. Titanosauriformes have a reduced manus ungual phalanx I (Salgado et al. 1997; Wilson and Sereno 1998), therefore it is possible that the trackmakers of G1 and G5 were basal neosauropods or eusauropods rather than derived neosauropods. Henderson (2006) proposed through his models and analyses, that wide gauge pattern in sauropods may be the consequence of the position of their centre of mass and body weight distribution. This author came to the conclusion that wide gauge trackways were produced by large sauropods weighing more than 12 tons and with more anteriorly-positioned centres of mass (which gave them stability). This situation could have occurred more than once in sauropod evolution (see Henderson 2006: fig. 13). This relationship between wide gauge sauropod trackways and anteriorisation of overall morphology has been also proposed by other authors (e.g., Lockley et al. 2002).

The trackways at the Galinha tracksite show sauropod features, namely a quadrupedal gait and huge manus and pes prints (Carrano and Wilson 2001; Wilson 2002, 2005). Moreover, both the manus and pes prints show features of the Eusauropoda (Carrano and Wilson 2001; Wilson 2002, 2005): a manus digit I with two phalanges including a large ungual phalanx; pes prints with a digit I mark larger and more deeply impressed than the other digit marks; pes prints showing a semi-digitigrade pes with metatarsal spreading; and deep impressions of the pedal ungual phalanges in the pes prints. The evidence of pedal ungual prints offset laterally is a feature described for *Barapasaurus* and more derived taxa (Wilson 2002, 2005). In the Galinha trackways, the pedal ungual prints III and IV face anterolaterally. All pedal ungual phalanges with anterolateral orientation, or claws II and III turned either directly laterally or almost posterolaterally, are seen in neosauropod forms (Bonnan 2005) and are probably traits of the Neosauropoda. In contrast the sauropod trackways at the Galinha tracksite have features that, according to Carrano and Wilson (2001) and Wilson (2002, 2005), suggest that the trackmakers were not neosauropods. The very large manus prints with evidence of digit marks, including a large digit I ungual phalanx, evidently exclude their having been made by Titanosauriformes and/or brachiosaurids (Farlow 1992 and Lockley et al. 1994a). Furthermore, Diplodocoidea, the sister group of Macronaria, includes clades such as Diplodocidae with small manus:pes size ratios (Lockley et al. 2002; Apesteguia 2005; Wright 2005). This also excludes these animals as the potential makers of these tracks. Moreover, the manus prints from the Galinha tracksite suggest a semi-tubular metacarpal arrangement that excludes Neosauropoda. The non-vertical arrangement of the metacarpals is consistent with large manus prints characterised by separate phalanges and a digit claw I mark oriented in a posterior-medial direction. This, however, excludes diplodocoids, camarasaurs, brachiosaurs and titanosaurs (Upchurch 1994, 1998; Wilson and Sereno 1998; Wilson and Carrano 1999; Apesteguía 2005; Carrano 2005) as the trackmakers. Although the wide gauge sauropod trackway pattern has previously been attributed to brachiosaurids (e.g., Lockley et al. 1994a) and to Titanosauriformes (e.g., Wilson and Carrano 1999) or Titanosaurs (Day et al. 2002) the presence of clear, wide gauge trackways in the Middle Jurassic strongly suggests this type of trackway pattern was not exclusive to titanosauriformes sauropods; the Galinha trackmakers and this last sauropod group clearly had a common locomotion pattern (wide gauge).

A wide gauge titanosaur trackway is represented by *Brontopodus birdi* from the Lower Cretaceous at Paluxy River, Dinosaur Valley State Park (USA) (described by Farlow et al. 1989). This trackway is distinctive in that the manus print length and width are about the same, the manus is clawless, somewhat U-shaped and with the impressions of digits I and V slightly separated from the impression of the conjoined digits II–IV; the pes prints are longer than broad, with large, laterally directed claw marks for digits I–III (digit marks IV and V only seen in well-preserved prints). The heteropody shown is high, with the pes area about 3 to 6 times larger that of the manus print area. The manus prints are rotated outward with respect to the direction of travel, and the manus print centres are somewhat closer to the trackway midline than the pes track centres.

Titanosauriformes and titanosaurs were responsible for *Brontopodus*-like wide gauge trackways due to their hind limb structure (Wilson and Carrano 1999). These animals existed from the Middle Jurassic (with trackways clearly attributed to these sauropods at Ardley Quarry, Oxfordshire, reported by Day et al. 2002) to the Upper Cretaceous (Wilson and Carrano 1999). Titanosauriformes such as *Lapparentosaurus madagascariensis* (Bonaparte 1986a; Upchurch et al. 2004) from the Bathonian of Madagascar, and the titanosaur *Janenschia robusta* (Bonaparte et al. 2000; Upchurch et al. 2004) from the Upper Jurassic of Tendaguru (Tanzania), were also wide gauge (*Brontopodus*-like) trackmakers.

Probably both the G1 and G5 trackways (Middle Jurassic of Portugal) represent wide gauge basal eusauropod trackways (*Polyonyx*-like). These both show asymmetric manus prints that are wider than long and that have a rounded lateral edge (digit mark V), a large digit I mark oriented in a posterior-medial direction, impressions of digits II–V, and a slightly bent metacarpal arch; the pes prints are longer than broad, oval shaped, toe-less impressions or with four claw marks (claws I–II with an anterior orientation; claws III–IV are laterally oriented). Their heteropody is low (the pes area is about twice the manus print area). Occasionally the manus print centres are closer to the trackway midline than the pes print centres. Both

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the manus and pes prints are rotated outward relative to the trackway midline. The characters of the wide gauge sauropod trackways at the Galinha site suggest that at least one basal eusauropod was able to produce wide gauge trackways. The osteological remains of basal eusauropods such as *Patagosaurus*, *Volkheimeria*, *Cetiosaurus*, *Cetiosauriscus*, and *Turiasaurus* (Upchurch et al. 2004; Royo-Torres et al. 2006) suggest they could have produced wide gauge trackways. They have some of the wide gauge trackmaker features described by Wilson and Carrano (1999), e.g., wider sacra, limb morphologies suggesting an angled posture, and increased eccentricity of the femoral midshaft. *Volkheimeria* (Bonaparte 1986b) and *Patagosaurus* (Bonaparte 1986b) show femora with the proximal part inclined medially, although they also show a lateral comb as in Titanosauriformes (Salgado et al. 1997). *Cetiosauriscus stewarti* Charig, 1980 (Woodward 1905: fig. 49), sometimes attributed to Diplodocoidea *incertae sedis* (Upchurch et al. 2004) but sometimes even exiled from Neosauropoda (Heathcote and Upchurch 2003), has a high eccentricity of the femoral midshaft similar to that seen in *Brachiosaurus* and *Saltasaurus* (Fig. 9).

The turiasaurs represent another group of basal eusauropods from the Middle Jurassic to Upper Jurassic–Lower Cretaceous boundary in Europe. The most complete taxon is *Turiasurus*, represented by manus and pes remains belonging to the same specimen (Royo-Torres et al. 2006). This seems to share features with the *Polyonyx* morphotype: a manus-pes area ratio of 1:2, a large manus digit I ungual phalanx (possibly articulated in a posterior position), and metatarsal V with a strongly expanded distal end that allows the impression of digit V to be made. Further, *Turiasaurus* has characteristics that could allow it to produce wide gauge trackways. For example, the proximal end of the humerus has a noticeable medial slant, similar to the femur of Titanosauriformes, and the femoral midshaft shows high eccentricity.

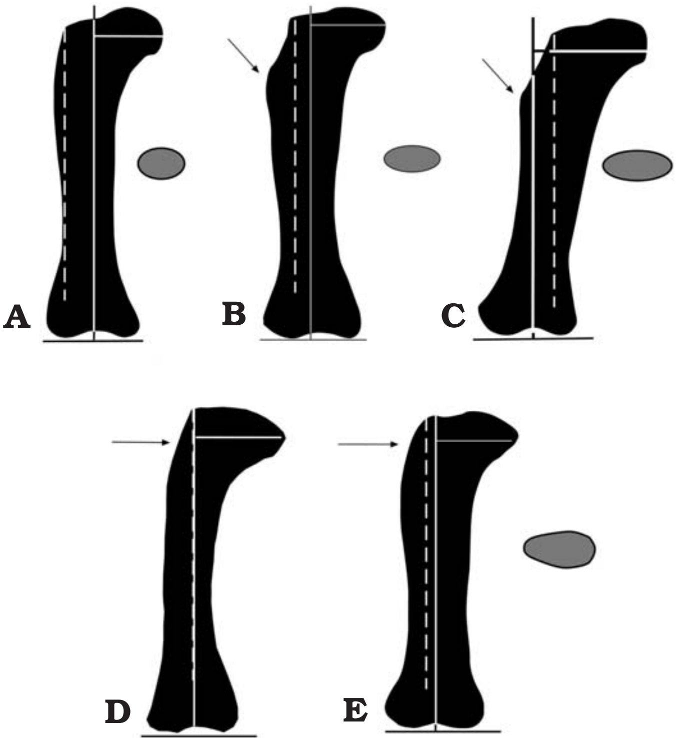

Fig. 9. **A**. Right femur of *Diplodocus* in anterior view. **B**. Right femur of *Brachiosaurus* in anterior view. **C**. Right femur of *Saltasaurus* in anterior view. **D**. Right femur of *Patagosaurus* in anterior view. **E**. Left femur of *Cetiosauriscus* in posterior view. A–C, after Wilson and Carrano (1999); D, after Bonaparte (1986b); E, after Woodward (1905).

Conclusions

At the Galinha tracksite there is an unequivocal evidence of wide gauge sauropod trackways produced by non-titanosauriformes. Their presence in the Middle Jurassic suggests that their sauropod makers were more widely distributed over time than previously thought. The proposed new ichnospecies *Polyonyx gomesi* igen. et isp. nov. is represented by a wide gauge sauropod trackway characterised by manus prints that are wider than long, and a large digit I mark oriented in a medial direction with a large, posteriorly oriented triangular claw mark. Digits II–V show a slightly bent arrangement. The pes prints show four claw marks, I–II with an anterior orientation, and III–IV laterally oriented. *Polyonyx* igen. nov. manus print morphology yields information about the display of the metacarpals and suggests an intermediate stage of manus structure between the non-tubular primitive sauropod manus and a tubular metacarpal distribution characteristic of more derived sauropods.

The Galinha tracksite is home to wide gauge trackways probably registered by a basal eusauropod and possibly a member of Turiasauria. We add a new ichno-morphotype, *Polyonyx*-like, to previous Sauropodomorpha subdivition now into five groups: *Tetrasauropus*-like, *Otozoum*-like, *Breviparopus/Parabrontopodus*-like, *Brontopodus*-like, and *Polyonyx*-like.

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References

Apesteguia, S. 2005. Evolution of the titanosaur metacarpus. *In*: V. Tidwell and K. Carpenter (eds.), *Thunder-Lizards, The Sauropodomorph Dinosaurs*, 321–345. Indiana University Press, Bloominton.

Azerêdo, A.C. 1993. *Jurássico médio do Maciço Calcário Estremenho (Bacia Lusitânica): análise de fácies, micropaleontologia, paleogeografia*. 403 pp. Unpublished Ph.D. thesis, Universidade de Lisboa, Lisboa.

Azerêdo, A.C., Ramalho, M.M., Santos, V.F., and Galopim de Carvalho, A.M. 1995. Calcários com pegadas de dinossáurios da Serra de Aire: microfácies e paleoambientes. *Gaia* 11: 1–6.

Avanzini, M., Leonardi, G., and Mietto, P. 2003. *Lavinipes cheminii* ichnogen., ichnosp. nov., a possible sauropodomorph track from the Lower Jurassic of the Italian Alps. *Ichnos* 10: 179–193.

Beaumont, G. and Demathieu, G. 1980. Remarques sur les extremites anterieures des Sauropodes (Reptiles, Saurischiens). *Comptes Rendus de l'Académie des Sciences* 15: 191–198.

Bonaparte, J.F. 1986a. The early radiation and phylogenetic relationships of the Jurassic sauropod dinosaurs, based on vertebral anatomy. *In*: K. Padian (ed.), *The Beginning of the Age of Dinosaurs*, 247–258. Cambridge University Press, Cambridge.

Bonaparte, J.F. 1986b. Los dinosaures (Carnosaures, Allosauridés, Sauropodes, Cétiosauridés) du Jurassique moyen de Cerro Cóndor (Chubut, Argentina). *Annales de Paléontologie* 72 (4): 247–289.

Bonaparte, J.F., Heinrich, W.D., and. Wild. R. 2000. Review of *Janenschia* Wild with the description of a new sauropod from the Tendaguru beds of Tanzania and a discussion on the systematic value of procoelous caudal vertebrae in the Sauropoda. *Palaeontographica* 256: 25–76.

Bonnan, M.F. 2003. The evolution of manus shape in sauropod dinosaurs: implications for functional morphology, forelimb orientation and phylogeny. *Journal of Vertebrate Paleontology* 23: 595–613.

Bonnan, M.F. 2005. Pes anatomy in sauropod dinosaurs: implications for functional morphology, evolution, and phylogeny. *In*: V. Tidwell and K. Carpenter (eds.), *Thunder-Lizards, The Sauropodomorph Dinosaurs*, 346–380. Indiana University Press, Bloominton.

Calvo, J. 1991. Huellas de dinosaurios en la Formación Río Limay (Albiano–Cenomaniano?), Picun Leufu, Provincia de Neuquén, Republica Argentina. *Ameghiniana* 28: 241–258.

Carrano, M.T. 2005. The Evolution of Sauropod Locomotion: morphological diversity of a secondary quadrupedal radiation. *In*: K.A. Curry Rogers and J.A. Wilson (eds.), *The Sauropods: Evolution and Paleobiology*, 229–251. University of California Press, Berkeley.

Carrano, M.T. and Wilson, J.A. 2001. Taxon distributions and the tetrapod track record. *Paleobiology* 27 (3): 564–582.

Christiansen, P. 1997. Locomotion in sauropod dinosaurs. *Gaia* 14: 45–75.

Dalla Vecchia, F.M. 1999. A sauropod footprint in a limestone block from the Lower Cretaceous of northeastern Italy. *Ichnos* 6: 269–275.

Dalla Vecchia, F.M. and Tarlao, A. 2000. New Dinosaur track sites in the Albian (Early Cretaceous) of the Istrian peninsula (Croatia). Parte II—Paleontology. *Memorie di Scienze Geologiche* 52: 227–292.

Day, J.J., Upchurch, P., Norman, D., Gale, A.S., and Powell, H.P. 2002. Sauropod trackways, evolution and behavior. *Science* 296: 1659.

D'Orazi Porchetti, S. and Nicósia, U. 2007. Re-examination of some large Early Mesozoic tetrapod footprints from the African collection of Paul Ellenberger. *Ichnos* 14: 219–245.

Dutuit, J.M. and Ouazzou, A. 1980. Découverte d'une piste de dinosaure sauropode sur le site d'empreintes de Demnat (Haut-Atlas Marocain). *Mémoire de la Société Géologique de France, New Series* 139: 95–102.

Ellenberger, P. 1972. Contribution à la classification des Pistes de Vertébrés du Trias: Les types du Stormberg d'Afrique du sud. (I partie). *Paleovertebrata, Mémoire extraordinaire, Montpellier* 104: 1–117.

Farlow, J.O. 1992. Sauropod tracks and trackmakers: integrating the ichnological and skeletal records. *Zubia* 10: 89–138.

Farlow, J.O., Pittman, J.G., and Hawthorne, J.M. 1989. *Brontopodus birdi*, Lower Cretaceous sauropod footprints from the U. S. Gulf coastal plain. *In*: D.D. Gillette and M.G. Lockley (eds.), *Dinosaur Tracks and Traces*, 371–394. Cambridge University Press, Cambridge.

Gierliński, G. 1997. Sauropod tracks in the Early Jurassic of Poland. *Acta Palaeontologica Polonica* 42: 532–537.

Ginsburg, L., Lapparent, A.F. de, Loiret, B., and Taquet, P. 1966. Empreintes de pas de Vertébrés tetrapodes dans les Séries continentales a l'Ouest d'Agades (Republique du Niger). *Comptes Rendus de l'Academie des Sciences* 263: 28–31.

Gomes, J.P. 1916. Descoberta de rastos de sáurios gigantescos no Jurássico do Cabo Mondego. *Comunicações Comissão Serviços Geológicos de Portugal* 11: 132–134.

Heathcote, J.F. and Upchurch, P. 2003. The relationships of *Cetiosauriscus stewarti* (Dinosauria; Sauropoda): implications for sauropod phylogeny. *Journal of Vertebrate Paleontology* 23 (3): 60A.

Henderson, D.M. 2006. Burly gaits: centers of mass, stability and the trackways of sauropod dinosaurs. *Journal of Vertebrate Paleontology* 26: 907–921.

Hendricks, A. 1981. Die Saurierfährten von Münchenhagen bei Rehburg-Loccum (NW-Deutschland). *Abhandlungen aus dem Landesmuseum für Naturkunde zu Münster in Westfalen* 43 (2): 1–22.

Huh, M., Hwang, K.G., Paik, I.S., Chung, C.H., and Kim, B.S. 2003. Dinosaur tracks from the Cretaceous of South Korea: Distribution, occurrences and paleobiological significance. *The Island Arc* 12: 132–144.

Ishigaki, S. 1988. Les empreintes de Dinosaures du Jurassique inférieur du Haut Atlas central marocain. *Notes et Mémoires Services Géologiques du Maroc* 334: 79–86.

Ishigaki, S. 1989. Footprints of swimming sauropods from Morocco. *In*: D.D. Gillette and M.G. Lockley (eds.), *Dinosaur Tracks and Traces*, 83–86. Cambridge University Press, Cambridge.

Leonardi, G. (ed.) 1994. *Annotated Atlas of South América tetrapod footprints (Devonian to Holocene)*. 248 pp. Companhia de Pesquisa de Recursos Naturais, Serviço Geológico do Brasil, Brasília.

Leonardi, G. and Mietto, P. (eds.) 2000. *Dinosauri in Italia*. 495 pp. Accademia Editoriale, Pisa-Roma.

Lim, S.-K., Lockley, M.G., Yang, S.-Y., Fleming, R.F., and Houck, K. 1994. *Brontopodus* and *Parabrontopodus* ichnogen nov. and the significance of wide-and narrow-gauge sauropod trackways. *Gaia* 10: 109–117.

Lires, J. 2000. *Icnitas de dinosaurios cuadrúpedos del Jurásico de Asturias. Morfometría, morfología e interpretación*. 62 pp. Memoria de Investigación, Universidade de Oviedo, Oviedo.

Lockley, M.G. and Meyer, C.A. 2000. *Dinosaur Tracks and other fossil footprints of Europe*. 323 pp. Columbia University Press, New York.

Lockley, M.G., Houck, K.J., and Prince, N.K. 1986. North America's largest dinosaur trackway site: implications for Morrison paleoecology. *Geological Society of America Bulletin* 97: 1163–1176.

Lockley, M.G., Farlow, J.O., and Meyer, C.A. 1994a. *Brontopodus* and *Parabrontopodus* ichnogen nov. and the significance of wide-and narrow-gauge sauropod trackways. *Gaia* 10: 135–145.

Lockley, M.G., Meyer, C.A., Hunt, A.P., and Lucas, S.G. 1994b. The distribution of sauropod tracks and trackmakers. *Gaia* 10: 233–248.

Lockley, M.G., Schulp, A.S., Meyer, C.A., Leonardi, G., and Mamani, D.K. 2002. Titanosaurid trackways from the Upper Cretaceous of Bolivia: evidence for large manus, Wide-gauge locomotion and gregarious behaviour. *Cretaceous Research* 23: 383–400.

Lockley, M.G., Wright, J.L., and Thies, D. 2004. Some observations on the dinosaur tracks at Munchehagen (Lower Cretaceous), Germany. *Ichnos* 11: 261–274.

Lockley, M.G., Lucas, S.G., and Hunt, A.P. 2006. *Evazoum* and the renaming of northern hemisphere "*Pseudotetrasauropus*": implications for tetrapod ichnotaxonomy at the Triassic–Jurassic boundary. *New Mexico Museum of Natural History and Science Bulletin* 37: 199–206.

Lockley, M.G., Lires, J., García-Ramos, J.C., Pinuela, L., and Avanzini, M. 2007. Shrinking the World's Largest Dinosaur Tracks: Observations on the Ichnotaxonomy of *Gigantosauropus asturiensis* and *Hispanosauropus hauboldi* from the Upper Jurassic of Asturias, Spain. *Ichnos* 14: 247–255.

Lockley, M.G., Kim, J.Y, Kim, K.S., Kim, S.H., Matsukawa, M., Rihui, L., Jianjun, L., and Yang, S.-Y. 2008. *Minisauripus*—the track of a diminutive dinosaur from theCretaceous of China and South Korea: implications for stratigraphic correlation and theropod foot morphodynamics. *Cretaceous Research* 29: 115–130.

Manuppella, G., Antunes, M.T., Almeida, C., Azerêdo, A.C., Barbosa, B., Cardoso, J.L., Crispim, J.A., Duarte, L.V., Henriques, M.H., Martins, L.T., Ramalho, M.M., Santos, V.F., and Terrinha, P. 2000. *Carta Geológica de Portugal (1/50 000), Notícia Explicativa da Folha 27-A (Vila Nova de Ourém)*. 156 pp. Instituto Geológico e Mineiro, Lisboa.

McIntosh, J.S. 1990. Sauropoda. *In*: D.B. Weishampel, P. Dodson, and H. Osmólska (eds.), *The Dinosauria*, 345–401. University of California Press, Berkeley.

Mensink, H. and Mertmann, D. 1984. Dinosaurierfährten (*Gigantosauropus asturiensis* n. g. n. sp.; *Hispanosaurus hauboldi* n.g. n.sp.) im Jura Asturiens bei La Griega und Ribadasella (Spanien). *Neues Jahrbuch für Geologie und Paläontologie* 7: 405–415.

Meyer, C.A., Lockley, M.G., Robinson, J.W., and Santos, V.F. 1994. A comparison of well-preserved sauropod tracks from the Late Jurassic of Portugal, and the western United States: Evidence and implications. *Gaia* 10: 57–64.

Moratalla, J.J., Mondejar, G.J., Santos, V.F., Lockley, M.G., Sanz, J.L., and Jiménez, S.J. 1994. Sauropod trackways from the Lower Cretaceous of Spain. *Gaia* 10: 75–83.

Nicosia, U. and Loi, M. 2003. Triassic Footprints from Lerici (La Spezia, Northern Italy). *Ichnos* 10: 127–140.

Rodrigues, L.A. and Santos, V.F. 2004. A Geometric Morphometrics Study on Sauropod Tracks. *In*: A.M.T. Elewa (ed.), *Morphometrics—Applications in Biology and Paleontology*, 129–143. Springer-Verlag, Heidelberg.

Romano, M. and Whyte, M.A. 2003. Jurassic dinosaur tracks and trackways of the Cleveland Basin, Yorkshire: preservation, diversity and distribution. *Proceedings of the Yorkshire Geological Society* 54: 185–215.

Romano, M., Whyte, M.A., and Manning, P.L. 1999. New sauropod dinosaur prints from the Saltwick Formation (Middle Jurassic) of the Cleveland Basin, Yorkshire. *Proceedings of the Yorkshire Geological Society* 52: 361–369.

Royo-Torres, R. Cobos, A., and Alcalá, L. 2006. A giant European dinosaur and a new sauropod clade. *Science* 314: 1925–1927.

Salgado, L., Coria, R.A., and Calvo, J.O. 1997. Evolution of titanosaurid sauropods. I: Phylogenetic analysis based on the postcranial evidence. *Ameghiniana* 34: 3–32.

Santos, V.F. 2003. *Pistas de dinossáurio no Jurássico–Cretácico de Portugal. Considerações paleobiológicas e paleoecológicas*. 365 pp. Unpublished Ph.D. thesis, Universidade Autónoma de Madrid, Madrid.

Santos, V.F. and Rodrigues, L.A. 2003. New data on Middle Jurassic Theropods from Portugal. 39 p. *51th Symposium of Vertebrate Palaeontology and Comparative Anatomy*. University Museum of Natural History, Oxford.

Santos, V.F., Lockley, M.G., Meyer, C.A., Carvalho, J., Galopim de Carvalho, A.M., and Moratalla, J.J. 1994. A new sauropod tracksite from the Middle Jurassic of Portugal. *Gaia* 10: 5–13.

Santos, V.F., Galopim de Carvalho, A.M., and Silva, C.M. da 1995. A jazida da Pedreira da Ribeira do Cavalo (Sesimbra) ou a história das pegadas de dinossáurio que nunca mais poderemos visitar. *Almadam, II Série* 4: 175–177.

Santos, V.F., Galopim de Carvalho, A.M., and Silva, C.M. da 1997. Pistas de Dinossáurios da Serra d'Aire-Jazida da Pedreira do Galinha. *Monumento Natural das Pegadas de Dinossáurio da Serra de Aire*, Bairro, 2pp.

Santos, V.F., Dantas, P., Moratalla, J.J., Araújo, M.G., and Galopim de Carvalho, A.M. 2000. Pegadas de terópodes em Alcanede, Portugal. *In*: J.B. Diez and A.C. Balbino (eds.), *I Congresso Ibérico de Paleontologia / XVI Jornadas de la Sociedad Española de Paleontología, Évora, Livro de Resumos*, 17. Universidade de Évora, Évora.

Santos, V.F., Rodrigues, L.A., and Alho, J.M. 2008. Middle Jurassic dinosaur tracksites from Portugal: where science meets natural heritage. *In*: A. Uchman (ed.), *The Second International Congress on Ichnology, Cracow, Poland, August 29-September 8, Abstract Book*, 113–114. Polish Geological Institute, Warsaw.

Schulp, A.S. and Brokx, W.A. 1999. Maastrichtian Sauropod Footprints from the Fumanya Site, Berguedŕ, Spain. *Ichnos* 6: 239–250.

Thulborn, R.A. 1990. *Dinosaur Tracks*. 410 pp. Chapman and Hall, London.

Upchurch, P. 1994. Manus claw function in sauropod dinosaurs. *Gaia* 10: 161–172.

Upchurch, P. 1998. The phylogenetic relationships of sauropod dinosaurs. *Zoological Journal of the Linnean Society* 124: 43–103.

Upchurch, P., Barrett, P.M., and Dodson, P. 2004. Sauropoda. *In*: D.B. Weishampel, P. Dodson, and H. Osmólska (eds.), *The Dinosauria (2nd edition)*, 259–322. University of California Press, Berkeley.

Vila, B., Oms, O., and Galobart, A. 2005. Manus-only titanosaurid trackway from Fumanya (Maastrichtian, Pyrenees): further evidence for an underprint origin. *Lethaia* 38: 211–218.

Whyte, M.A. and Romano, M. 2001. Probable stegosaurian dinosaur tracks from the Saltwick Formation (Middle Jurassic) of Yorkshire, England. *Proceedings of the Geologists' Association* 112: 45–54.

Wilson, J.A. 2002. Sauropod dinosaur phylogeny: critique and cladistic analysis. *Zoological Journal of the Linnean Society* 136: 215–275.

Wilson, J.A. 2005. Overview of Sauropod Phylogeny and Evolution. *In*: K.A. Curry Rogers and J.A. Wilson (eds.), *The Sauropods: Evolution and Paleobiology*, 15–49. University of California Press, Berkeley.

Wilson, J.A. and Carrano, M.T. 1999. Titanosaurs and the origin of "wide-gauge" trackways: a biomechanical and systematic perspective on sauropod locomotion. *Paleobiology* 25: 252–267.

Wilson, J.A. and Sereno, P. 1998. Early evolution and higher level phylogeny of sauropod dinosaurs. *Journal of Vertebrate Paleontology* 18 (2): 1–68.

Woodward, A.S. 1905. On parts of the skeleton of *Cetiosaurus leedsi*, a sauropodous dinosaur from the Oxford Clay of Peterborough. *Proceedings of the Zoological Society of London* 1: 232–243.

Wright, J.L. 2005. Steps in Understanding Sauropod Biology: the importance of sauropod tracks. *In*: K.A. Curry Rogers and J.A. Wilson (eds.), *The Sauropods: Evolution and Paleobiology*, 252–284. University of California Press, Berkeley.

EM PORTUGUÊS

OS SEGREDOS DA NOSSA CULTURA GEOGRÁFICA

PALEONTOLOGIA

Pelo Dedo se Vê o Gigante!

O primeiro monumento natural de pegadas de dinossauro foi classificado há dez anos, mas desde 1996 que a conservação e museolização das jazidas portuguesas cai em sucessivos alçapões. No campo, os paleontólogos inventam novas formas de estudar pegadas.

Texto de Gonçalo Pereira
Fotografias de Luís Quinta

O Centro de Acolhimento do Monumento Natural das Pegadas de Dinossauro da Serra de Aire, projectado pelo arquitecto J.P. Martins Barata, é o ex-líbris dos museus de ar livre dedicados à observação de pegadas de dinossauro.

EM PORTUGUÊS

"Doutora, vem ver as *patas*?", pergunta, sorridente, o senhor Domingos, no restaurante O Cocheiro, a meia dúzia de quilómetros de Fátima, região de forte pulsar religioso, para onde acorrem anualmente seis milhões de peregrinos. O restaurante é uma réplica de uma cavalariça e o senhor Domingos, orgulhoso, confessa que até já foi figurante no filme "Aparição", de 1992. Como bom anfitrião, porém, ele está também à vontade para discutir dinossauros, a outra força motora da região.

A "doutora" é Vanda Santos, a única investigadora portuguesa especializada em paleoicnologia (o estudo das marcas fósseis da actividade de seres vivos) e figura incontornável do processo de conservação do Monumento Natural de Pegadas de Dinossauro da Serra de Aire (MNDPDSA). Aos poucos, o trabalho da *doutora das pegadas* foi assimilado pelas comunidades onde o destino fez caminhar os gigantes do passado há milhões de anos. As "patas" são a forma carinhosa de este empresário local agradecer o movimento económico gerado pelos 23 mil visitantes anuais do monumento.

Tudo começou em 1994. O espeleólogo João Carvalho descobriu pegadas de saurópode na pedreira de Rui Galinha, uma próspera exploração que alimentava de brita várias empreitadas de auto-estradas em Portugal. Vanda Santos ainda se lembra do dia em que recebeu o telefonema sugerindo uma visita à pedreira. "Transportei os instrumentos tradicionais para uma intervenção de emergência", conta. "Pensei que encontraria duas ou três pegadas, faria moldes do que visse e fotografaria o local para registo. Nunca me passou pela cabeça que uma pedreira daquela magnitude pudesse ser parada."

A família italiana Bartolucci é o protótipo do visitante tradicional de Ourém: veio para visitar Fátima, mas não quis deixar de ver as famosas pegadas de dinossauro.

À força de dinamite, perfurando de dez em dez metros, a pedreira chegara a um estrato do Jurássico com pegadas. Operários espiavam os movimentos da paleontóloga com minúcia enquanto camiões carregavam brita, alheios ao que se desenrolava mais abaixo. "Estava tanta gente sobre a laje que eu só via pessoas. Não via pegadas", conta ela. A observação cuidada do local, porém, constituiu a surpresa de uma vida. No perímetro que escolheu para amostra, sempre que limpava a laje, identificava novas pegadas. Entusiasmada, Vanta Santos pegou no giz e tentou encontrar pegadas do mesmo animal.
Um dos trilhos, claramente de um grande herbívoro, parecia não ter fim. Inesperadamente, Vanda Santos ajudara a descobrir o maior trilho de saurópodes da Europa (147 metros) e um dos mais bem conservados do mundo.

Seguiu-se um longo processo de negociação entre o Estado e o empresário, que culminou na aquisição do terreno por uma verba próxima dos cinco milhões de euros e na classificação, em 1996, do local como Monumento Natural. Galopim de Carvalho, professor jubilado da Faculdade de Ciências de Lisboa e ex-director do Museu Nacional de História Natural (MNHN), lembra que o preço não foi o negócio milionário que se temeu. "Houve quem escrevesse que se pagou de mais por um local daqueles. Eu creio que nem o negócio foi assim tão milionário (quase metade da verba foi retida de imediato pelos serviços fiscais), nem um bem cultural pode ser caro de mais. Penso até que tivemos sorte por lidar com um empresário com tanto respeito pelo património."

Pouco depois, fruto do entusiasmo gerado pelos dinossauros,

Ourém

É a jazida mais importante do país e aquela que está mais bem preparada para receber visitantes. Contém uma das pistas de saurópodes mais longas e bem conservadas do mundo.

PERÍODO JURÁSSICO MÉDIO
DATAÇÃO 170 MILHÕES DE ANOS
GRUPOS SAURÓPODES
ESTATUTO MONUMENTO NATURAL (1996)
DESTAQUE UMA PISTA DE SAURÓPODE COM 147 METROS DE COMPRIMENTO.

A Ciência das Pegadas

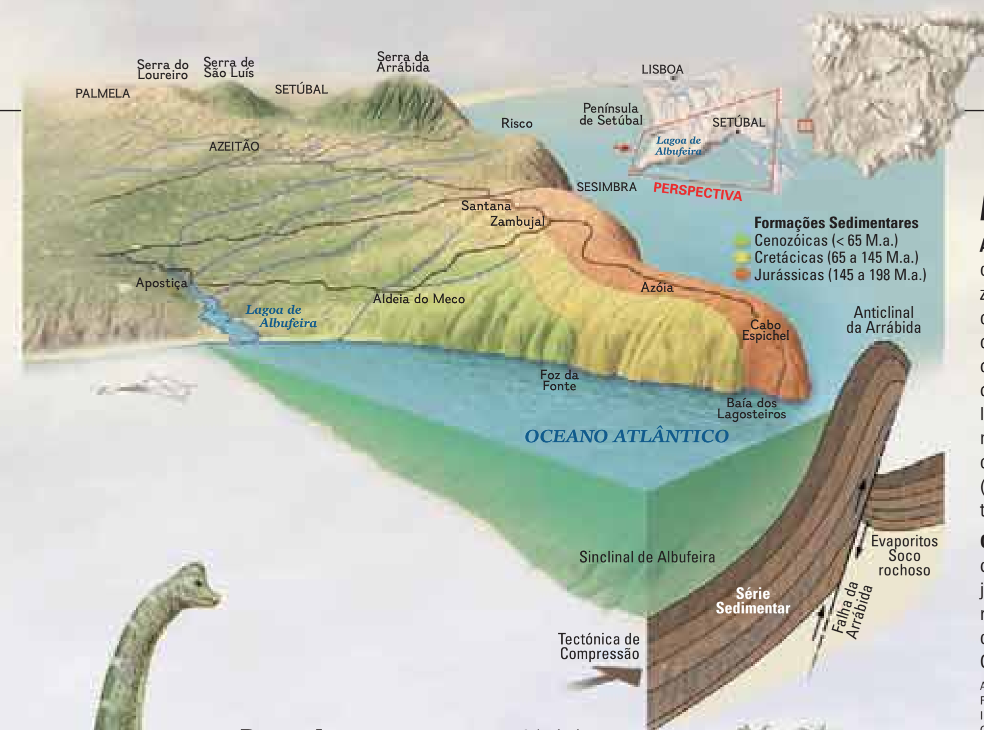
Interpretar a rocha para descobrir os gigantes.

As jazidas com pegadas do cabo Espichel possuem indicadores de comportamento gregário: trilhos paralelos regularmente espaçados, revelando o mesmo sentido de progressão, e pegadas de dimensões idênticas onde se estimaram velocidades de deslocação semelhantes. Exemplos como os desta ilustração, extrapolada a partir de informação da baía dos Lagosteiros, são interpretados como evidências de comportamento gregário. Desta forma, é possível conhecer hábitos de vida de organismos que não pertencem à fauna actual.

As pistas paralelas da praia dos Lagosteiros constituem o primeiro exemplo de comportamento gregário nos saurópodes na Europa, bem como o melhor testemunho conhecido entre animais tão jovens.

Mãe Galinha

Nesta reconstituição, um adulto *Brachiosaurus* segue sete juvenis. Os actuais conhecimentos comportamentais permitem afirmar que os dinossauros eram progenitores extremosos. As pegadas paralelas dos sete juvenis e de um adulto levam-nos a inferir que estaríamos perante uma "cena de família". Estes dinossauros eram verdadeiros gigantes entre gigantes, atingindo centenas de toneladas de peso e uma altura de cerca de 15 metros. Os braquiossáurios pertenciam ao grupo dos saurópodes e viveram no Jurássico.

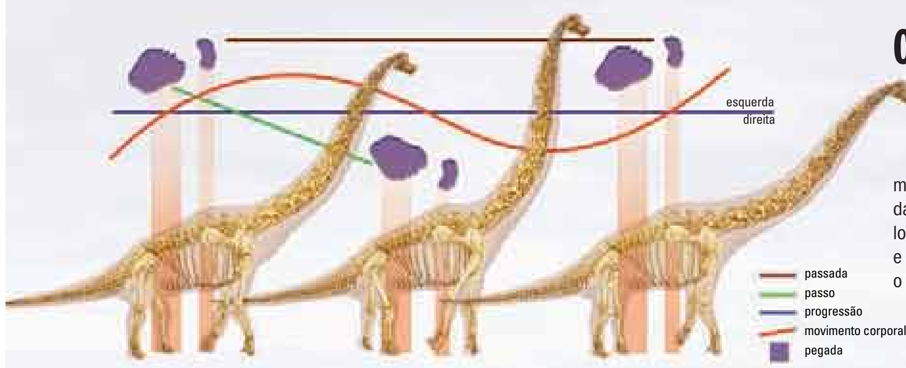


A Arrábida

As forças tectónicas podem dobrar camadas depositadas em planos horizontais e originar estruturas tectónicas como a chamada "monoclinal" do Espichel. Esta corresponde ao flanco longo de uma dobra cujo eixo se situa a sul da linha de costa e está associada à falha da Arrábida. A deformação é miocénica, distinguindo-se dois episódios compressivos principais: no Burdigaliano (21,8 a 16,6 milhões de anos) e no Tortoniano superior (8 a 6,5 Ma).

O pendor das camadas diminui gradualmente para norte: varia desde 70º junto ao farol, atinge 45º nos Lagosteiros até que, na Foz da Fonte, o Miocénico se sobrepõe aos calcários do Cenomaniano em ligeira discordância.

A ESCALA VARIA COM A PERSPECTIVA
FONTES: KULLBERG, KULLBERG E TERRINHA (2000) IN *MEM. GEOCIÊNCIAS*, MNHN, Nº2, 35-84; CARTA LITOLÓGICA (1982) IN *ATLAS DO AMBIENTE*



Como os Elefantes

Os paleontólogos que estudam a locomoção dos saurópodes usam como modelo biológico o elefante na estrutura dos membros e das patas. As pegadas permitem estabelecer a sequência de contacto das patas com o solo e perceber o tipo de locomoção. Assim, as pegadas vão condicionar e aferir a informação dos ossos e completam o *puzzle* da deslocação destes animais.

Pegadas com Milhões de Anos

Tectónica As lajes de calcário que limitam a sul a praia dos Lagosteiros formaram-se na horizontal há cerca de 145 milhões de anos **(1)**. Nesta área, existia uma extensa superfície litoral plana e alagada, com sedimentos finos não consolidados e com alguma plasticidade, onde os dinossauros deixaram rastos.

Ao longo do tempo Acumularam-se dezenas de metros de espessura de sedimentos que hoje constituem as camadas sedimentares desta região **(2)**, muitas das quais apresentam na superfície rastos de dinossauros **(3)**.

Moldes e contramoldes Ao passarem em sedimentos lamacentos e carbonatados, os animais deixaram as suas pegadas, isto é, deixaram no solo a impressão ou o molde do pé ou da mão **(A)**. Por vezes, as camadas inferiores também ficam deformadas e conservam as subimpressões.
Os sedimentos que cobrem as impressões constituem a camada superior e na sua base exibem em relevo os preenchimentos dos moldes: os contramoldes.

ARTE DE FERNANDO CORREIA E NUNO FARINHA
CONSULTORES: VANDA SANTOS E LUÍS RODRIGUES (MUSEU NACIONAL DE HISTÓRIA NATURAL DA UNIVERSIDADE DE LISBOA)

Um testemunho da passagem de um grupo de sete pequenos saurópodes seguido por três indivíduos de grandes dimensões ficou preservado na arriba que limita a sul a praia dos Lagosteiros e que constitui a jazida da Pedra da Mua. As sete pistas são paralelas e revelam que os animais de menores dimensões viajavam a cerca de 5km/h. Os adultos deixaram também pistas paralelas entre si e passaram depois porque as pegadas de um deles se sobrepõem às dos juvenis.

FONTE: LOCKLEY, MEYER E SANTOS (1994) IN *GAIA*, N.º10, 27-35

Um molde de gesso produzido por um entusiasta reforça a necessidade de vigilância destes museus ao ar livre.

que tinha motivado a maciça adesão de 360 mil visitantes a uma exposição do MNHN, a pedreira tornou-se o primeiro parque paleontológico nacional, símbolo do carinho que os portugueses sentem por tudo o que diga respeito aos dinossauros.

Actualmente, de um dos miradouros entretanto criados, a uma altura de quase trinta metros, observam-se a olho nu as diversas pistas de dinossauro que constituem a riqueza do local. Paralelo, um rasto mais moderno é igualmente observável no calcário – o rasto dos milhares de visitantes que, acompanhando as pegadas, desgastam lentamente a rocha e criam novas necessidades de conservação. São as dores de crescimento de um parque moderno.

Seguramente que o geólogo Jacinto Pedro Gomes não imaginava, em 1884, que uma fracção tão considerável da população se interessaria pelos estranhos animais cujos vestígios contemplava então. No cabo Mondego, a poucos quilómetros da Figueira da Foz, o geólogo foi chamado para observar fósseis encontrados pelos trabalhadores de uma mina de carvão. Para seu espanto, vislumbrou pegadas, que validavam as extrapolações que já então se faziam das dimensões gigantescas dos animais do Jurássico. A descoberta, que Jacinto Pedro Gomes se apressou a comunicar a colegas belgas e alemães (embora o relatório do achado só tenha sido publicado postumamente), é a jazida com pegadas de dinossauro que há mais tempo se conhece em Portugal e um dos primeiros estudos no mundo sobre o tema.

Luís Rodrigues, paleontólogo do MNHN, é um herdeiro moderno do geólogo oitocentista. Munido de um computador e de uma aplicação informática que permite transformar qualquer objecto numa realidade tridimensional, este doutorando dá nova vida aos dinossauros. Vida digital, entenda-se. Quantificando as diferenças morfológicas e combinando a informação dos membros com as pegadas deixadas na rocha, Luís Rodrigues espera criar a primeira base de dados evolutivos de morfometria geométrica 3-D dos fósseis das principais colecções paleontológicas do mundo. Do Carnegie Museum à Patagónia, ansiando pelos afamados museus chineses, o investigador tem pela frente a tarefa de encontrar as formas prováveis dos fósseis (e das pegadas) mais bem conservados(as) do mundo. "A paleontologia evoluiu imenso desde o século XIX, mas o trabalho de campo continua genericamente o mesmo", diz.

Prova desta máxima é o entusiasmo de Vanda Santos enquanto limpa afanosamente o calcário de uma laje em Vale de Meios (Rio Maior), trabalho aparentemente enfadonho mas potencialmente frutífero. Onde o olho leigo vê uma ligeira depressão, a paleontóloga antevê informação. De certa forma, o especialista em paleoicnologia não é muito diferente do guia indígena, que lê nas pegadas o número de feras das redondezas e o seu comportamento recente. Porém, quando se investiga o Jurássico Médio, há muito que as feras abandonaram o terreno.

Pontualmente considerada como parente pobre da paleontologia, sem o encanto táctil dos ossos fossilizados, a paleoicnologia fornece todavia informação comportamental. A pegada é parte de uma sequência. Isolada, tem valor relativo, como uma moeda romana descontextualizada. Se bem conservada, permite saber a identidade do animal, as suas dimensões e a forma do pé ou mão que a deixou. Uma pista, porém, revela dados sobre o modo de locomoção: a postura do membro, o sentido e a velocidade de deslocação. Em jazidas como a dos Lagosteiros (cabo Espichel), onde se observam sete trilhos paralelos de saurópodes, é possível extrapolar que eles seguiam em manada. "É fascinante imaginar comportamentos gregários baseados na informação impressa na rocha. Normalmente, essa informação comportamental não pode ser fornecido pela osteologia", diz a paleontóloga.

Em Ourém, um dos trilhos é foco de interessante polémica,

Praia da Salema

Extremamente bem conservadas, as pegadas do Algarve, como as da praia da Salema, fornecem informações únicas sobre ornitópodes iguanodontídeos do Cretácico.

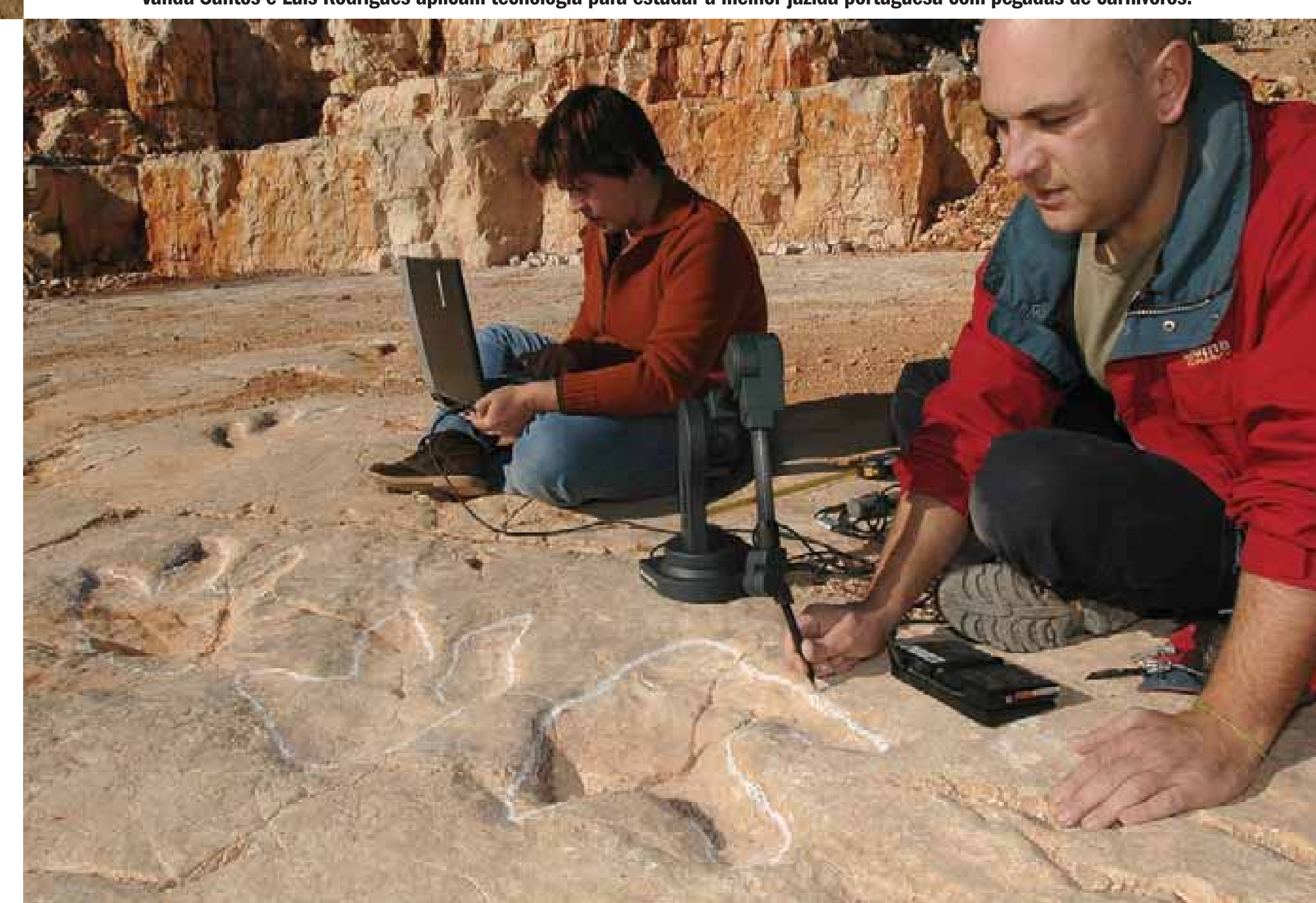
PERÍODO CRETÁCICO INFERIOR
DATAÇÃO 125-130 MILHÕES DE ANOS
GRUPOS TERÓPODES E ORNITÓPODES
ESTATUTO NÃO TEM PROTECÇÃO
DESTAQUE UMA PISTA DE IGUANODONTÍDEO COM 2,20 METROS ATÉ À ANCA

Vale de Meios

Com centenas de pegadas de carnívoros, esta jazida justifica melhor conservação e valorização monumental.

PERÍODO JURÁSSICO MÉDIO
DATAÇÃO 170 MILHÕES DE ANOS
GRUPOS TERÓPODES
ESTATUTO IMÓVEL DE INTERESSE MUNICIPAL (2003)
DESTAQUE RARO CONJUNTO DE DEZENAS DE PISTAS PARALELAS DE CARNÍVOROS

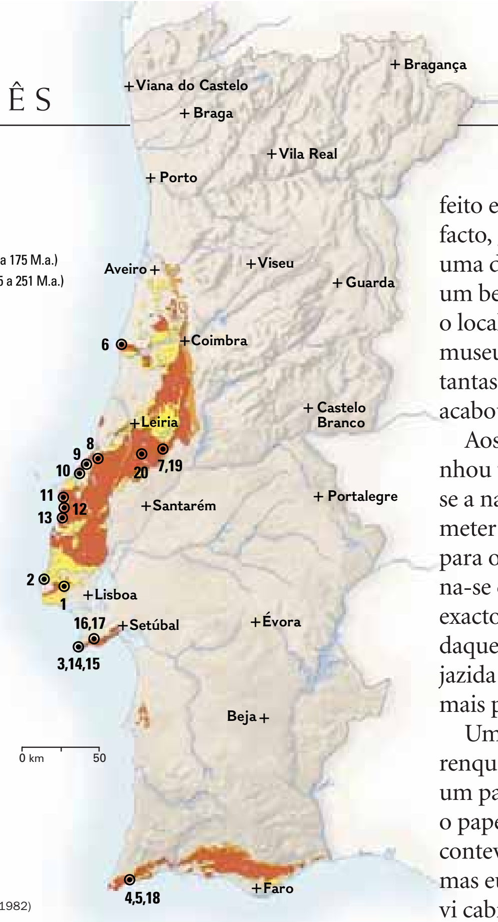
Vanda Santos e Luís Rodrigues aplicam tecnologia para estudar a melhor jazida portuguesa com pegadas de carnívoros.



Jazidas de pegadas em Portugal

- ◉ Locais com pegadas de dinossauros
- Terrenos do Cretácico (65 a 145 M.a.)
- Terrenos do Jurássico Superior e Médio (145 a 175 M.a.)
- Terrenos do Jurássico Inferior e Triássico (175 a 251 M.a.)
- ● Pegadas de Terópodes (carnívoros)
- ● Pegadas de Ornitópodes (herbívoros)
- ● Pegadas de Saurópodes (herbívoros)

	Terópodes	Ornitópodes	Saurópodes
Cretácico Superior			
1. Pego Longo - Carenque	●	?	
Cretácico Inferior			
2. Praia Grande	●		●
3. Lagosteiros	●	?	
4. Praia da Salema	●	●	
5. Praia Santa		●	
Jurássico Superior			
6. Cabo Mondego	●		
7. Pedreira / Amoreira	●		
8. Serra da Pescaria			●
9. São Martinho do Porto	●	●	●
10. Pedras Negras	●		●
11. Pai Mogo	●		
12. Praia da Areia Branca	●	?	
13. Praia da Corva	●		
14. Pedra da Mua	●		●
15. Praia do Cavalo	●		
16. Pedreira da Rib. do Cavalo	●		●
17. Pedreira do Avelino			●
18. Foia do Carro			●
Jurássico Médio			
19. Pedreira do Galinha			●
20. Pé da Pedreira	●		



MAPA: NUNO FARINHA E FERNANDO CORREIA
FONTES: LOCKLEY ET AL (1994) E CARTA LITOLÓGICA (1982)

pois o animal abrandou o passo metros antes de se cruzar com o trilho mais longo. Teria o animal abrandado à vista do outro bem maior? "Ninguém o pode afirmar com total certeza, porque não temos meios de saber se as pegadas foram produzidas no mesmo dia ou na mesma semana. Mas a discussão abre um campo aliciante sobre o comportamento dos grandes saurópodes."

Se o Monumento Natural de Ourém é metaforicamente a batalha de Aljubarrota da paleontologia portuguesa, a jazida de Pego Longo (Carenque) é a batalha de Alcácer-Quibir, o desfecho de que poucos se querem lembrar. Descoberto em 1986, há precisamente 20 anos (ironicamente, uma efeméride que poucos comemorarão), apesar da fraca qualidade do calcário margoso da região, ali se conservou o trilho de um provável ornitópode. Com 95 milhões de anos, as pegadas são as mais recentes do Cretácico em Portugal.

Em 1992, depois de o anúncio do traçado da Circular Regional Exterior de Lisboa (CREL) configurar a destruição a prazo da jazida, Galopim de Carvalho lançou mãos à obra e mobilizou apoios para uma batalha inesquecível. O cordão humano de 600 crianças gritando "Salvem as Pegadas" tornou-se a imagem de marca do protesto. Por fim, a gigantesca barreira política que ameaçava a jazida colapsou. Por quase dez milhões de euros, o Estado português construiu um túnel para a CREL, mantendo incólumes as pegadas, e classificou, em 1997, o local como Monumento Natural. A vitória, porém, foi pírrica.

A museolização do espaço nunca foi financiada, e o MNHN manteve as pegadas cobertas com geotêxtil e por uma camada de 20 a 30cm de terra. Ironicamente, as pegadas tiveram de ficar enterradas para seu próprio bem! A avaliação de Galopim de Carvalho soa tristemente a um *requiem* pela oportunidade perdida: "Hoje, mais de uma década depois, teria feito exactamente o mesmo. De facto, ganhámos: reinvertemos uma decisão política e salvámos um bem cultural. Mas é pena que o local nunca tenha recebido o museu projectado. Ocorreu o que tantas vezes sucede em Portugal: acabou-se o dinheiro!"

Aos poucos, a vegetação ganhou terreno sobre a jazida, como se a natureza conspirasse para remeter as pegadas cada vez mais para o centro da Terra. Hoje, torna-se difícil descobrir o ponto exacto onde se situam os trilhos daquela que é, sarcasticamente, a jazida portuguesa mais cara. E a mais próxima da capital.

Um dia, nas imediações de Carenque, Vanda Santos encontrou um pastor que, esclarecido sobre o papel da paleontóloga, não se conteve: "A doutora vai desculpar, mas eu ando aqui há 40 anos e só vi cabras, ovelhas e vacas por estes montes. Esses bichos eu nunca vi!" Como se vê, o papel pedagógico da jazida de Carenque, explicando e mostrando o mundo dos dinossauros, tarda em consumar-se.

Nem tudo, porém, se perdeu. A poucos metros da jazida, foi atribuído o nome de Galopim de Carvalho a uma nova escola de ensino básico em reconhecimento pelos serviços do geólogo à região. Simbolicamente, talvez os adultos do futuro ali formados possam reinverter o desfecho da batalha de Carenque. ◻

Pedra da Mua

Impressionantes pela sua envolvência, as jazidas do cabo Espichel aguardam há décadas pela museolização.

PERÍODO JURÁSSICO SUPERIOR
DATAÇÃO 145 MILHÕES DE ANOS
GRUPOS TERÓPODES E SAURÓPODES
ESTATUTO MONUMENTO NATURAL (1997)
DESTAQUE UMA PISTA DE UM SAURÓPODE COXO (COM PASSO IRREGULAR)

Sem condições de segurança para visitas e sem informação básica de divulgação, as pegadas do cabo Espichel aguardam há duas décadas por uma intervenção autárquica. Até lá, são um património restrito aos aventureiros.

ENVOLVIMENTO POPULAR

Paixão e Criatividade

Como o estranho mundo dos dinossauros inspira autodidactas de norte a sul do país

José Joaquim tem 55 anos e é carpinteiro em Casalinhos de Alfaiata, a escassos quilómetros de Torres Vedras. Em 1986, precisamente no ano em que dois alunos finalistas da Faculdade de Ciências de Lisboa (Carlos Coke e Paulo Monteiro) identificaram um trilho na pedreira da Quinta de Santa Luzia, em Pego Longo (Carenque), José Joaquim iniciou o seu ritual domingueiro. Sob o sol inclemente ou fustigado pela água da chuva, o carpinteiro selecciona uma rota e caminha com lentidão. Invariavelmente, o seu olhar, treinado por duas décadas de prospecção, perscruta o terreno como uma peneira. Onde muitos veriam apenas uma arriba, José Joaquim pressente um campo inesgotável de materiais.

Os paleontólogos do Museu Nacional de História Natural tinham-nos alertado para a surpresa que a visita à oficina de José Joaquim despertaria. A princípio, o alerta soou a uma espécie de praxe aos jornalistas. Fora da estrada principal, porém, uma tabuleta chama os visitantes para o "Pno. Museu Vivo Pré-Histórico". Franqueada a porta, eis uma das mais fantásticas colecções privadas de fósseis do país.

Cada material tem um curto letreiro, referenciando a data e o local da colheita. Na memória de José Joaquim, porém, cada fóssil ganha uma história de carne e osso. "Quando encontrei este dente, virei-me para o Sol e dei graças por este momento. Não se encontram dentes todos os dias", diz.

"Esta cabeça de fémur foi a minha primeira descoberta. Nem sabia bem o que era. Encontrei-a no alto de Santa Rita", recorda sem se deter. "Este outro vi-o num dia de maré inesperadamente baixa. Estava fragmentado em quatro pedaços incrivelmente conservados. Trazê-los pela arriba acima foi um trabalho dos diabos!"

José Joaquim personifica o entusiasmo que os dinossauros geraram em miúdos e graúdos nas últimas duas décadas. À medida que foram dadas a conhecer jazidas, autodidactas como este carpinteiro torrejano cultivaram a sua paixão e ajudaram a desvendar um mundo que permanece literalmente soterrado sob camadas de sedimentos. Claro está que há colheitas… e colheitas. Devidamente enquadrado pelo MNHN, José Joaquim construiu uma colecção admirável.

À saída, a pergunta é inevitável: "No letreiro, 'Pno.' é diminutivo de quê?"

"De Pequeno. Pequeno Museu Vivo Pré-Histórico", responde. "Toda a vida fui modesto."

Torres Vedras

De dentes a garras, de fémures a vértebras, há um pouco de tudo na colecção privada de José Joaquim. Nos últimos 20 anos, o coleccionador perscrutou as arribas da região torrejana em busca de fósseis de dinossauro. Apesar da dimensão da colecção, José Joaquim ainda sonha com um fóssil que completasse a amostra como uma cereja no topo do bolo. "Um dia, gostava de encontrar ovos de dinossauro."

Carenque

Descoberta em 1986 e classificada em 1997, a jazida de Carenque está tapada. Da presença de dinossauros, resta apenas esta homenagem em cimento de um construtor local.

PERÍODO **CRETÁCICO SUPERIOR**
DATAÇÃO **95 MILHÕES DE ANOS**
GRUPOS **TERÓPODES E ORNITÓPODE (?)**
ESTATUTO **MONUMENTO NATURAL (1997)**
DESTAQUE **UMA DAS LONGAS PISTAS DE DINOSSAURO DO CRETÁCICO**

Cimento em Carenque

Em Carenque, já se viu, as pegadas são uma memória recente que as voltas e revoltas da política reenviaram para debaixo da terra. A escassos metros da jazida tapada, porém, entre terrenos baldios e montes de entulho vazado sem rei nem roque, um particular construiu em cimento a sua própria visão do mundo dos dinossauros (em cima).

Anunciada por um letreiro garrafal que chama ao local "A Toca dos Dinossauros", uma curta faixa de terreno é sobrepovoada por pequenos dinossauros de cimento. Anatomicamente incorrectos, estes são os únicos vestígios do entusiasmo que varreu Carenque em meados da década de 1990, quando os planos de museolização do trilho conhecido mais perto de Lisboa captaram o imaginário desta localidade encaixada entre os concelhos da Amadora e de Sintra.

Para já, porém, estes são os únicos dinossauros que emergiram da toca. Os outros permanecem tristemente tapados.

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