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New Permian tetrapod footprints and macroflora from Turkey (Çakraz Formation, northwestern Anatolia): Biostratigraphic and palaeoenvironmental implications

Nouvelles traces de pas de tétrapode et macroflore permiennes de Turquie (Formation de Çakraz, Anatolie nord-occidentale) : implications biostratigraphiques et paléoenvironnementales

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ABSTRACT

New tetrapod footprints belonging to the ichnogenus *Hyloidichnus* have been discovered in Turkey for the first time, in the lower part of the Çakraz Formation (Northwestern Anatolia) and together with macrofloral imprints of *Annularia* and *Stigmaria*. These discoveries confirm the Permian age of the fossiliferous red beds in which the coniferophyte *Walchia* was previously recorded. Based on the stratigraphic range of *Annularia*, *Stigmaria* and *Hyloidichnus* known elsewhere, a Cisuralian age is proposed for these beds. These new ichno- and macrofloral remains, together with the sedimentological data (mudcracks, rain drops) suggest the presence of captorhinid reptiles living in a palustrine floodplain environment, and under a warm, seasonal climate alternating between humid and relatively long dry seasons. These climatic conditions may have permitted the migration of these captorhinids through Laurasia during the Permian.

RÉSUMÉ

Pour la première fois, des traces de pas de vertébrés attribuées à l'ichnogenre *Hyloidichnus* sont découvertes en Turquie, associées à des empreintes de macroflore du genre *Annularia* et *Stigmaria*. Ces fossiles proviennent de la partie inférieure de la Formation de Çakraz, dans laquelle furent mentionnés auparavant des restes de *Walchia*. D'après la répartition stratigraphique d'*Annularia*, de *Stigmaria* et d'*Hyloidichnus*, un âge Cisuralien est proposé

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pour ces niveaux. Cet assemblage ichno- et paléobotanique, combiné aux données sédimentologiques (fentes de dessiccation, gouttes de pluie) suggère la présence de reptiles captorhinidés évoluant dans un environnement de plaine d'inondation à zones palustres et végétalisées, sous climat chaud et saisonnier avec des alternances de périodes humides et sèches. Ces conditions climatiques ont peut-être favorisé la migration trans-laurasiatique de ces reptiles au cours du Permien.

1. Introduction

Turkey is a complex orogenic mosaic consisting of various amalgamated continental fragments located along suture zones resulting from the closing of different oceanic realms, the latest being the Neotethys. The Istanbul Zone is one of the six major continental fragments in Turkey: about 400 × 70 km in size, it is located along the southwestern margin of the Black Sea (Fig. 1). This zone is separated from the Sakarya Zone to the South, from the Intra-Pontide suture to the East, and from the Thrace Zone to the West by what may be a buried transform fault – the western Black Sea Fault. Compared to the surrounding continental fragments, the Istanbul Zone shows a distinct geology in which a Precambrian crystalline basement is overlain by a deformed – but not metamorphosed – transgressive Palaeozoic succession extending from the Ordovician to the Carboniferous (Aydın et al., 1986; Dean et al., 1997; Görür et al., 1997; Sengor and Ozgul, 2010). It is followed by a compressional deformation that generated intensive folds and thrusts (Zabcı et al., 2003). The deformed Palaeozoic rocks are intruded by Late Permian granites east of Istanbul (Yılmaz, 1977; Yılmaz-Şahin et al., 2009) and are unconformably overlain by Triassic clastic rocks. This brackets the age of the deformation between the post-Westphalian and the pre-Late Permian.

The Permo-Triassic sequence of the Istanbul Zone shows facies differences from west to east. To the west, in the Bythnian Peninsula, it comprises an 800 m transgressive, then regressive sequence dated from the Earliest Scythian to the Norian (Assereto, 1972; Gedik, 1975; Yurtttaş-Özdemir, 1973). To the east, between Düzce and Cide, the Permo-Triassic sequence is represented by continental red to variegated sandstones and conglomerates: the Çakraz Formation.

Until now, no fossil remains have been found in the Çakraz Formation, except *Walchia* remnants discovered by Grancy (1938, unpublished report) that suggested a possible Permian age. The discovery of footprints and macroflora by our team confirms this age and allows us to specify it

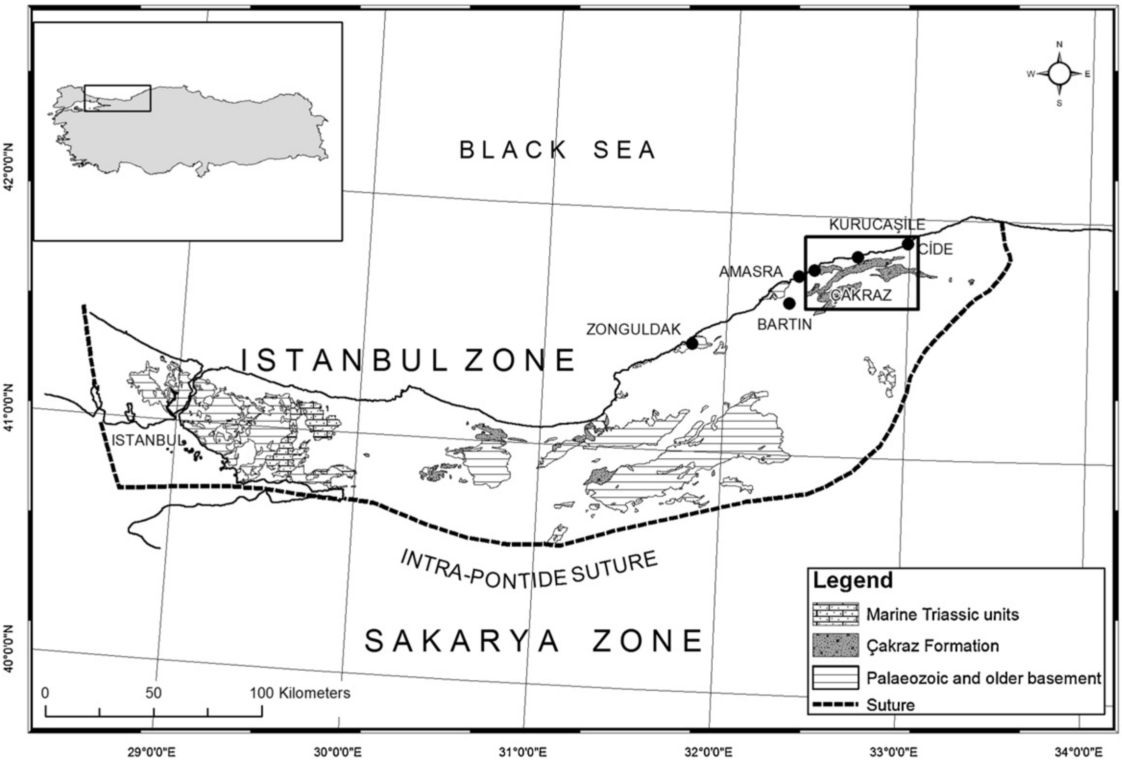

Fig. 1. The Palaeozoic and the Permo-Triassic outcrops of the Istanbul Zone. Rectangle shows the location of Fig. 2.
Fig. 1. Affleurements paléozoïques et permo-triasiques de la zone d'Istanbul. Le rectangle localise l'espace de la Fig. 2.

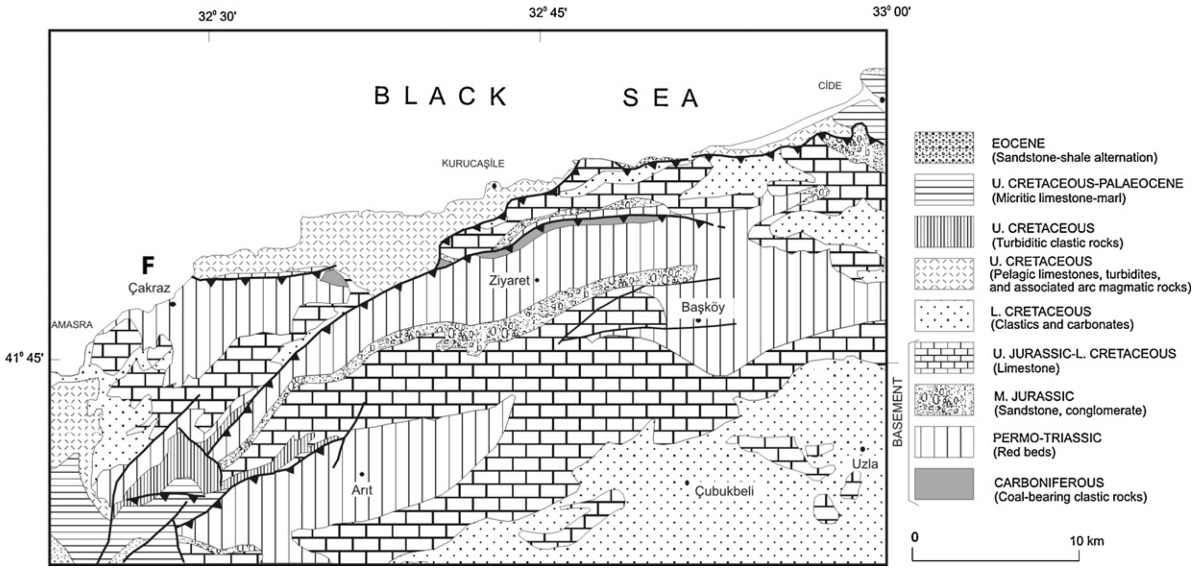

Fig. 2. Geological map of Amasra-Çakraz-Cide region (Tüysüz et al., 1997). The fossiliferous site F is on the Black Sea shore of the Çakraz Village.

Fig. 2. Carte géologique de la région d'Amasra-Çakraz-Cide (Tüysüz et al., 1997). Le site fossilifère F est localisé sur le rivage de Çakraz.

with greater precision. It is also the first time that fossil tetrapod footprints have been discovered in Turkey. The Çakrazboz Formation, conformably overlying the Çakraz Formation, yielded a Latest Triassic flora (Akyol et al., 1974; Alişan and Derman, 1995) (Figs. 2 and 3).

The aims of this article are therefore, after placing these new fossils in their geological and stratigraphic contexts:

- to describe the new fossils: footprints and macroflora;
- to provide a new age for the Çakraz Formation;
- to describe the palaeoenvironmental and palaeoclimatic contexts of the deposits.

2. The Çakraz Formation

The Çakraz Formation is represented by very thick (>3000 m) continental clastic redbeds including conglomerates, sandstones and mudstones (Fig. 3). The best preserved and the most continuous sections of this formation outcrop along the Black Sea shore, from south of Kızılburun and Ovadere, east of the village of Çakraz, and the Değirmendere valley (Fig. 2). It rests unconformably on the Carboniferous clastic beds east of Çakraz Bay, and is unconformably overlain by Middle Jurassic and younger units (Akman, 1992; Tüysüz et al., 1997, 2000). Most parts of the formation are represented by red to purple clastic beds, with greenish and whitish laterally continuous horizons. Grancy (1938) described six horizons within the Çakraz Formation, numbered p1 to p6 sequentially:

- *Member p1.* The base of the Çakraz Formation is represented by red conglomerates in which most of the pebbles are Devonian limestones and Carboniferous clastic elements. Coal fragments are visible within the conglomerates. Their thickness ranges from 25 to 100 m. Cross-channel structures and the texture of the pebbles indicate a possible braided river palaeoenvironment.

- *Member p2.* The conglomerates are overlain by red to brownish sandstones alternating with mudstones corresponding to the p2 Horizon. Wedding (1970) mentioned *Walchia* remains in this horizon and therefore suggested a possible Permian age for it. The footprints *Hyloidichnus* and the new macroflora (*Annularia, Stigmaria*) described here come from this horizon (Steyer et al., 2006) (F, Fig. 3). Thin- to medium-bedded sandstones are well sorted and rich in quartz. Tabular and trough type cross-bedding in the sandstones, as well as mudcracks in the mudstones, are common. Sandstones and alternating mudstones of this horizon were probably deposited in a fluvial system. The thickness of this horizon varies between 400 and 600 m.

East of Çakraz Bay, high-angle large-scale cross-bedded siltstones and fine-grained sandstones are well cropped. The thickness of the cross-bedding sets can exceed 2 m. Palaeocurrent directions estimated from these cross-beddings are multidirectional. Sands and silts are well sorted, rounded and weakly consolidated. They probably indicate an eolian depositional environment. This horizon sits on a sandstone layer, and is overlain by floodplain deposits as well as following lacustrine sediments. These eolian deposits were developed locally and reach 100 m in thickness.

- *Members p3 and p4.* These horizons are represented by mudstones dominated by red, green and yellowish clasts, with common calcretes. Most of the green and yellowish colors of Member p3 result from weathering or hydrothermal activity along the fracture zones. Within the mudstones, some sandstone and conglomerate

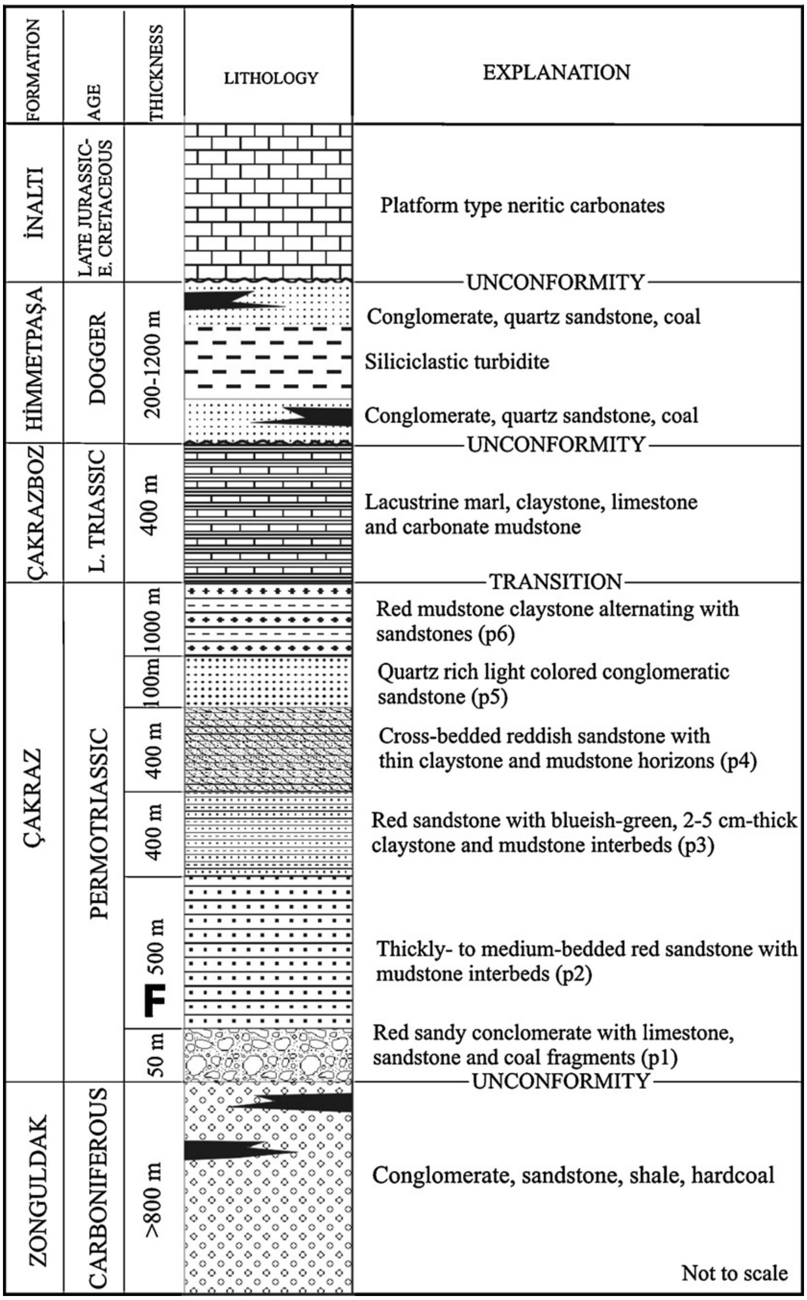

Fig. 3. Pre-Cretaceous generalized columnar section of the Amasra-Çakraz-Cide region. F = fossiliferous level.

Fig. 3. Colonne stratigraphique anté-Crétacé de la région d'Amasra-Çakraz-Cide. F = niveau fossilifère.

horizons are visible. Clasts of these horizons are well rounded, badly sorted and matrix supported. There is no clear difference between p2 and p3 horizons except some colour changes. Both horizons are dominated by red mudstones consisting of ripple-marks, raindrop marks, tool-marks, sand-filled mudcracks and other sedimentary structures indicating a floodplain palaeoenvironment. Cross-bedded sand and conglomerate dominated parts of these horizons probably represent meandering river deposits. The total thickness of these meandering river and floodplain deposits exceeds 1200 m.

The floodplain deposits are overlain by light red to brown, quartz-rich, thick bedded to massive, well sorted, medium to coarse-grained, cross-bedded sandstones with local conglomeratic horizons. Mudstone horizons alternating with sandstones are common. These deposits are locally visible south of Çakraz and Kurucaşile.

- *Members p5 and p6.* Member p5 is mostly represented by quartz rich light colored conglomeratic sandstones. Member p6 is represented by light-coloured quartz rich conglomeratic sandstones, reaching 100 m in thickness. The uppermost part of the formation is formed by 200 to 1000 m thick red mudstones and sandstones similar to horizons p2 and p3. In this uppermost part, outcropping south of Çakraz and Kurucaşile, white marls and claystones are visible. These 10–30 cm thick white horizons alternate with red mudstones and claystones. They increase upward in thickness and frequency.

The lacustrine sediments overlaying the Çakraz Formation yielded freshwater algae and palynomorphs, indicating a Late Triassic age (Alişan and Derman, 1995). Rutherford et al. (1992; unpublished report, British Petroleum) also found Late Triassic palynomorphs in this horizon.

In the Çamdağ area, northeast of Adapazarı, similar red beds rest unconformably on Palaeozoic sediments and are unconformably overlain by Cretaceous sediments (Kipman, 1974; Alişan and Derman, 1995). The last authors described a rich terrestrial palynomorph assemblage from the dark shales alternating with redbeds. Based on this observation, they dated these deposits as Late Permian.

3. The new ichnofossils and macroflora

Three slabs numbered "Çakraz 01 to 03" are described below. They are housed in the Geology Department of the Technical University of Istanbul, Turkey.

3.1. Ichnites (Figs. 4–5)

3.1.1. Hyloidichnus sp. (Çakraz 01 slab footprint, Figs. 4.1, 4.2)

A manus–pes couple (abbreviated "PMC") is very well preserved, in convex hyporelief, on a red micaceous silstone slab (10 × 10 × 4 cm). In section, the slab shows an elementary sequence ended by a brown pellicular mudstone bed.

The imprint of the pes is pentadactylous and semi-plantigrade, a little longer (L) than broad (W) (L × W = 24 × 22 mm). The straight toes bear few claw impressions. They are spread out from digits I to IV, but IV is a little longer than III. The lengths of the digits are: I = 10 mm, II = 15 mm, III = 17 mm, IV = 19 mm, V = 12 mm. The distal ends of digit impressions I, IV, and V are Y-shaped. The pads are well marked. The manus imprint is located 35 mm ahead of the pes. It is digitigrade but digits I and II are broken (Fig. 4.2). The distal end of digit IV is covered by a thin siltstone layer. The distal imprint of digit V is located laterally at the rear of digits I–IV. Based on the size of the digit III, the total length of the hand could be assessed to 19 mm. Thus, it would be 1.26 times smaller than the pes.

The rigid aspect of the digital traces, some with a relatively forked or Y-shaped distal end, is the main characteristic of the ichnogenus *Hyloidichnus*. It was defined by Gilmore (1927) based on the ichnospecies *Hyloidichnus bifurcatus* (Fig. 4.4) from the base of the Hermit Shale Formation (Arizona, USA).

Compared with the holotype of *H. bifurcates* (which preserves two complete PMC), the *Hyloidichnus* pes from Turkey shows clearly longer (approximately 50%) impressions of V-shaped toes. But without a larger sample of footprints, it is impossible to know whether this difference is significant. We prefer therefore to present the Turkish footprints merely as *Hyloidichnus* sp.

Hyloidichnus also occurs in other countries such as:

- France: in several basins of the Massif Central (Demathieu et al., 1992; Gand, 1987; Gand and Durand, 2006). It is particularly abundant in the Lodève Basin where the largest *Hyloidichnus* are 120 mm long;
- Germany: *H. arnhardti* Haubold, 1973 (synonym of *Amphisauripus kablikae* per Voigt, 2004) and *H. microdactylus* (Gand, 1987) are known from the Thuringian Forest. *Hyloidichnus* is probably also present in the Saar-Nahe Basin (Gand and Durand, 2006);
- Poland: *H. arnhardti* has been described by Ptaszyński and Niedźwiedzki (2004) in the Slupiec Formation (Early Permian);
- Italy: *Hyloidichnus* has been identified by Conti et al. (1977) and Ceoloni et al. (1988) in the Bolzano Basin, although Avanzini et al. (2001) did not mention it in their list of ichnotaxa;
- Spain: Gand et al. (1997) identified the ichnogenus in the Permian of Peña Sagra, Cantabria;
- Morocco: large (10 cm long) *Hyloidichnus* footprints are common in the Permian Tiddas Basin. First discovered by Broutin et al. (1987), they were collected in 2000 by Gand (during a fieldtrip of the Permian Geologists Association) and later by Hmich et al. (2006) and Voigt et al. (2010).

According to Haubold (1971), *Hyloidichnus* was ascribed to "Diadectosauria" (for diadectomorphs), then to Captorhinomorpha. From well-preserved footprints and trackways of *Hyloidichnus major* from the USA, the autopodial skeleton of the trackmakers was inferred and then compared to various skeletons of Permian reptiles and parareptiles (Carroll, 1988; Heaton and Reisz, 1980). The assignment of *Hyloidichnus* as captorhinomorph footprints was confirmed by Gand (1987: 156–157). Within this group, the footprint morphology matches relatively well with the skeletons of *Labidosaurus* from the Clear-Fork Formation and/or *Captorhinus* from the Wichita Formation, both from the Lower Permian (Sakmarian-Artinskian) of the USA (Modesto and Smith, 2001). *Captorhinus* and *Labidosaurus* have a pedal phalangeal formula (from digits I to V, by convention) of 2-3-4-5-4 and *Captorhinikos* of 2-3-4-5-3 (e.g., Holmes, 2003; Olson, 1962). The inferred formula of the *H. major* trackmaker is 2-3-4-5-4 or 2-3-4-5-3 (Gand, 1987). It is similar to *Hyloidichnus* sp. from the Permian of Turkey: digit V appears to have either three or four phalanges.

3.1.2. Slab "Çakraz 02"

This reddish micaceous siltstone slab is 43 × 24 cm in size. The ichnofossiliferous surface is composed of a polygonal network of mudcracks filled with fine sandstones forming crossed cords of 1 cm width (Figs. 4, 5).

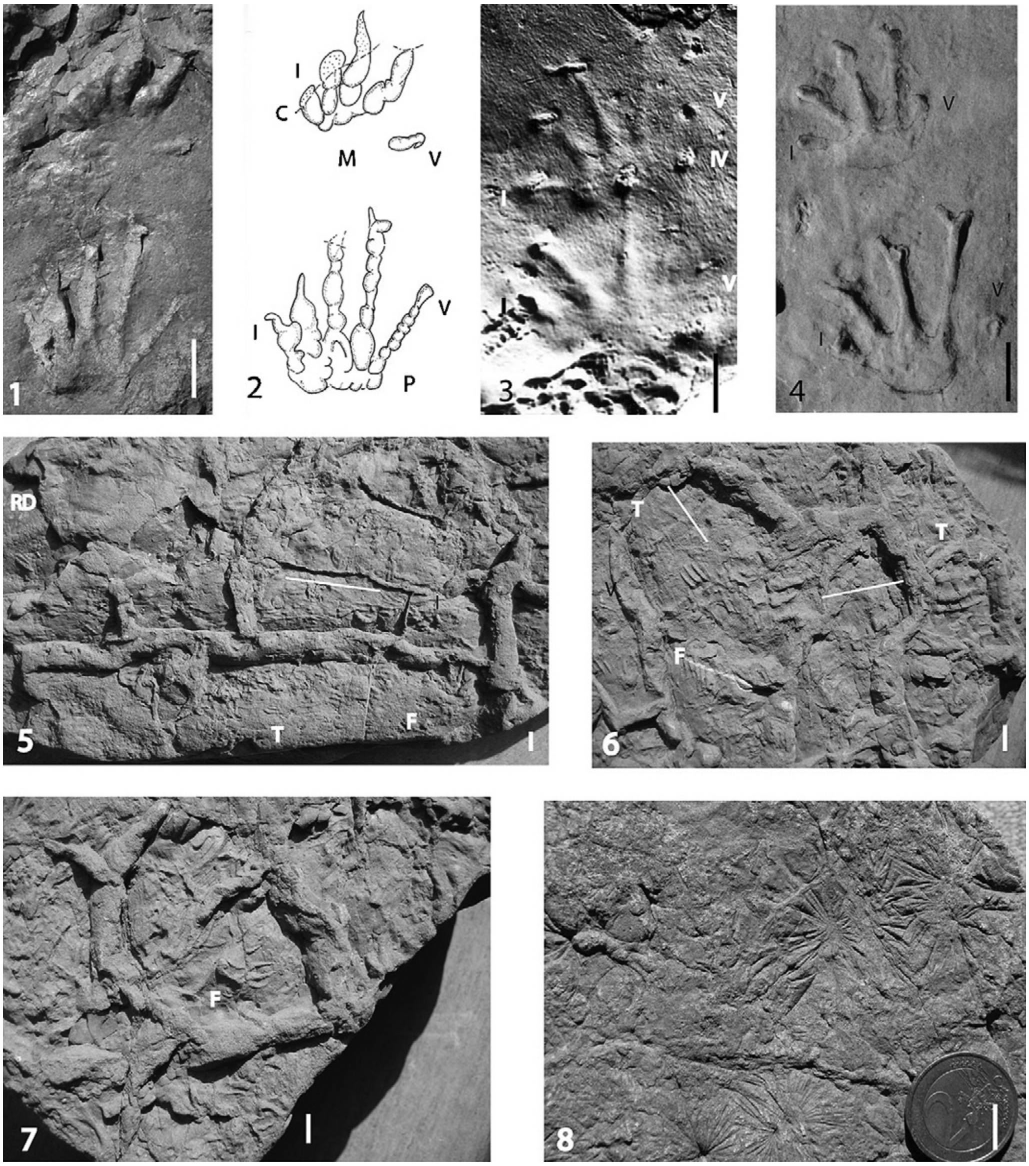

Fig. 4. *Hyloidichnus***: 1–2**: Pes (**P**) and manus (**M**); **I–V**: digit number of *Hyloidichnus* sp. from the Permian Çakraz Formation, Turkey; **3**: *Hyloidichnus major* (pes–manus) from the Permian of France; **I**, **IV**, **V**: digit number; **4**: *Hyloidichnus bifurcates* (holotype pes–manus) from the Hermit Shale Formation of USA; **5–7**: Zooms of the zones A, B and C from the slab "Çakraz 02" (Fig. 5); **T**: digit scratches; **F**: footprints; **RD**: raindrop traces; **8**: *Annularia stellata* from the Permian Çakraz Formation, Turkey. Scale bar 1 cm.

Fig. 4. *Hyloidichnus* : **1–2** : pied **(P)**-main (**M**) ; **I–V** : numéros des doigts de *Hyloidichnus* sp. du Permien de Turquie, Formation de Çakraz ; **3** : couple pied–main de *Hyloidichnus major* du Permien français ; **4** : couple pied–main de *Hyloidichnus bifurcatus* de la Formation Hermit Shale, USA (holotype) ; **5–7** : agrandissement des parties A, B et C de la dalle « Çakraz 02 » (Fig. 5) ; **T**, **F**, **RD** (respectivement) : traces de griffures, de pas et de gouttes d'eau ; **8** : *Annularia stellata* du Permien de Turquie, Formation de Çakraz. Barre d'échelle 1 cm.

On remaining smooth areas, convex hyporelief traces are visible, including well-preserved isolated footprints (Figs. 4.5, 4.7 F). In this case, the metapodial and basipodial traces are not distinguishable: they consist of an oval unit extended distally by relatively subparallel griffoid digit marks. They could be interpreted as swimming trackways, more or less continuous, with parallel rectilinear to sinuous furrows. These furrows could be the digital end marks left by animals swimming in shallow waters.

Animals moved in two perpendicular directions, *x* towards *y*, and *w* towards *z* (Figs. 4.6, 5.2). These trackways, left on an immersed sediment, are rather frequent in the Permian (Gand, 1987, pl. 5E) and are preserved thanks to cyanobacterial activity (Gand et al., 2008).

3.2. Macroflora (Fig. 4.8)

Centimetric and indeterminate wood fragments are visible in the slab section of "Çakraz 02" and on the

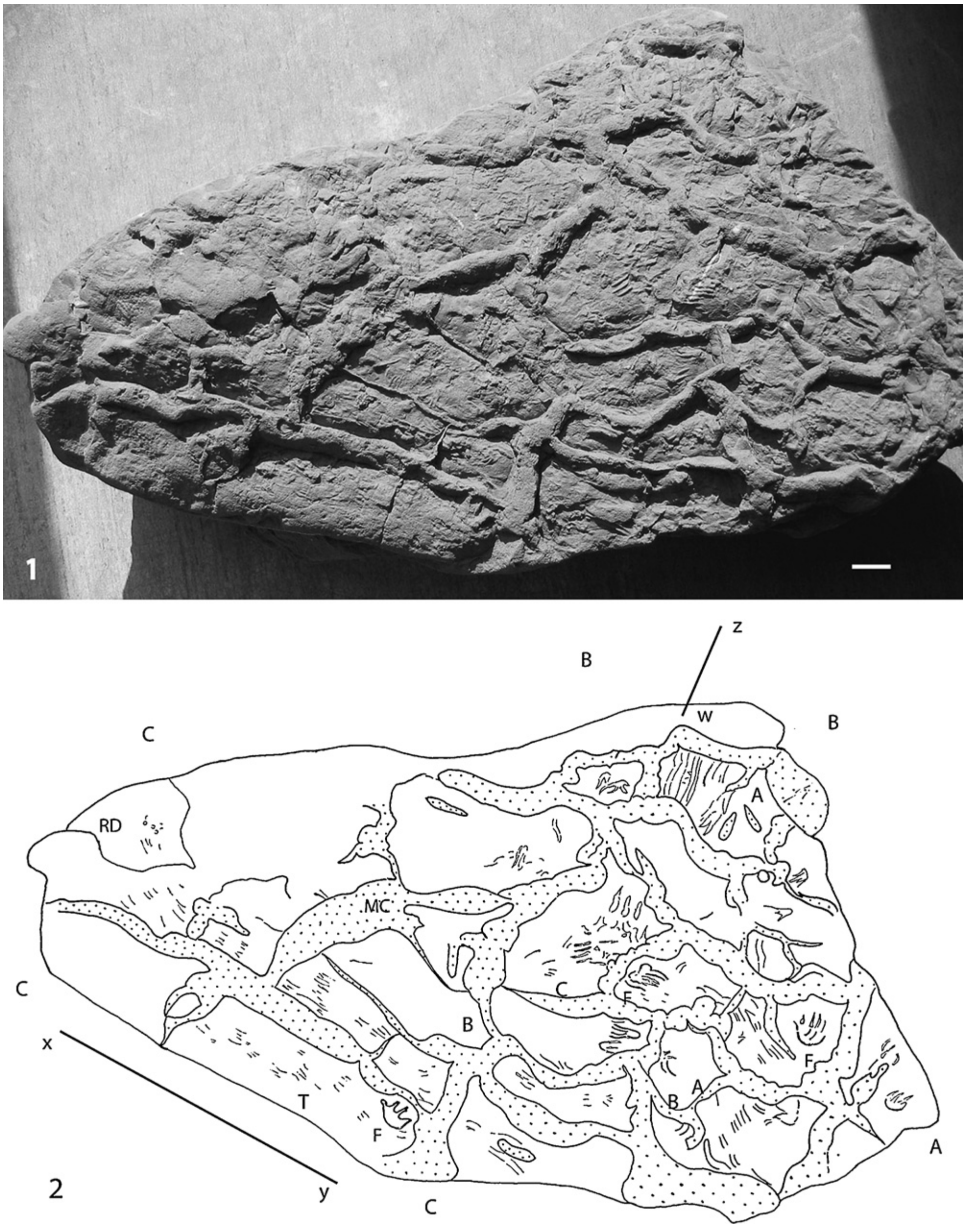

Fig. 5. *Hyloidichnus* sp. from the Permian Çakraz Formation, Turkey, Slab Nr. "Çakraz 02": **1**: Hyporelief face; **2**: schematic interpretation; **x–y, z–w** strokes: two swim trackway directions; **A**, **B**, **C**: zooms of Fig. 4; **MC**: mudcracks; **T, F, RD**: acronyms, see caption Fig. 4. Scale bar 1 cm.

Fig. 5. *Hyloidichnus* sp. du Permien de Turquie, Formation de Çakraz, dalle numérotée « Çakraz 02 » : **1** : Surface à hyporeliefs ; **2** : Schéma interprétatif ; traits **x–y** et **z–w** : traces de nage dans deux directions ; **A**, **B**, **C** zooms de la Fig. 4 ; **MC** : fentes de dessiccation ; **T**, **F**, **RD** : acronymes voir légende Fig. 4. Barre d'échelle 1 cm.

surface of "Çakraz 03" (not figured), both found in the same layer as the footprint slabs "Çakraz 01 and 02". Numerous foliage imprints are identified as *Annularia* aff. *radiata* (according to M. Berthelin) or/and *Annularia stellata* (according to GG) (Fig. 4.8). These Calamariaceae belong to the Carboniferous-Permian Euramerican equatorial floral province. *Stigmaria*-like impressions (root systems of arborescent lycophytes) were also determined by M. Berthelin.

4. Palaeoclimate and palaeoenvironment of the macroflora-footprints association, and Pangaean implications

The footprints are connected with mudcracks in the same layer interfaces, suggesting that tetrapods progressed in a shallow and often emerged zone. They probably belong to the captorhinid group, which may have ventured especially onto floodplain overbanks. The *Annularia* foliages

(Calamariaceae) also suggest a palustrine zone. Frequent mudcracks and raindrop traces, associated with the red colour of the sediments, suggest a general hot and wet climate alternating with dry seasons. This is also indicated by the occurrence and palaeoecological needs of *Walchia*. This palaeoclimatic context is regularly observed in Permian red bed formations of many Euramerican regions such as southern France and Morocco (Broutin et al., 1987; Châteauneuf and Farjanel, 1989; Larhrib, 1996).

The trackways discovered in the Çakraz Formation are the first fossil tetrapod footprints known in Turkey, and the easternmost occurrence of the ichnogenus *Hyloidichnus* on Pangaea. This has important palaeobiogeographic implications because the global distribution of reptiles during the Permian is mostly documented by skeletal remains rather than ichnofossils (e.g., Steyer, 2009a). Body fossils of captorhinids and other reptiles are also known in the Permian of Asia (e.g., Reisz et al., 2011 for China; Steyer, 2009b for synapsids from Laos). The Turkish *Hyloidichnus* therefore links western and eastern Laurasia, and suggests that these small and gracile tetrapods crossed Pangaea by following a Eurasian migration route. This trans-Laurasian migration route was located along the North Tethyan coast (based on the position of northern Turkey during the Permian according to Sarıbudak et al., 1989; Scotese, 2001). The reptiles that colonized Asia may have preferred this route rather than a southern Gondwanian one (like the Tethyan south coast) probably because of its more favourable and subtropical climatic conditions as suggested by our palaeoclimatic interpretations.

5. Biostratigraphy

Hyloidichnus is only known in the Permian, where it has a variable vertical range (Gand and Durand, 2006: 170). In France, it is only observed in the second sedimentary cycle ("Saxonian" Group = Rabejac and Salagou formations) dated differently according to the markers used: ashes, insects, footprints, conchostracans and macroflora. In a synthetic study, Lopez et al. (2008) demonstrated that the "Saxonian" in the Lodève Basin covers an interval ranging from the Artinskian to the Lower Lopingian.

In the USA, the holotype of *Hyloidichnus* recovered from the Hermit Shale Formation is dated to the Lower Artinskian (Gilmore, 1927; Haubold and Lucas, 2001). Later on, *Hyloidichnus* was also found in the older Hueco Formation of Robledo Mountains, dated to the Sakmarian (Haubold and Lucas, 2001). However, most of these footprints termed "*Hyloidichnus*" are not well identified, except one (NMMNHP-23088), which "provides unequivocal obviousness for the presence of *H. bifurcatus* in the Hueco" (Haubold et al., 1995: 145).

The large vertical range of *Hyloidichnus* between the Sakmarian and the Guadalupian (Wordian) in France (Gand and Durand, 2006) does not allow the use of this ichnogenus as a fine stratigraphic marker. It is the same for *Annularia stellata*, which is known from the Gzelian to the Cisuralian in the Euramerican Floral Province zone (Lemoigne, 1988) to which Turkey belongs.

6. Conclusions

The footprints of *Hyloidichnus* as well as the *Annularia* and *Stigmaria* macroflora confirm the Permian age of the fossiliferous beds of the Çakraz Formation, as suggested by Grancy (1938) from the recovery of *Walchia*. Taking into account their stratigraphic range, a Cisuralian age is suggested for the Çakraz Formation Member p2.

Palaeontological and sedimentological data from the fossiliferous Çakraz Formation deposits indicate that captorhinid reptiles lived in palustrine Equisetophytina-Lycopodiophytina zones belonging to a floodplain palaeoenvironment. The climate was humid and hot, i.e. (sub)tropical, with long dry seasons as shown by the red beds and the occurrence of *Walchia*. These climatic conditions may have allowed the migration of these captorhinid reptiles through Laurasia.

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