doi: 10.3304/jmes.2020.17068

Journal of Mediterranean Earth Sciences 12 (2020), 1-12
In: Romano M., Citton P. (Eds.), Tetrapod ichnology in Italy: the state of the art

Journal of Mediterranean Earth Sciences

Tetrapod ichnology in Italy: the state of the art
Guest editorial

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ABSTRACT - This year, 2020, marks the 150th anniversary of the seminal work by Giulio Curioni (1870), representing the first published scientific contribution on tetrapod footprints from Italy. We took this opportunity to discuss the current state of the art on tetrapod ichnology in our country, with a jubilee volume, titled "*Tetrapod ichnology in Italy: the state of the art*". The volume involves the scholars who first pioneered this discipline in Italy in the seventies of the last century, along with all the authors who have worked on the topic in recent decades, and younger generations who have just started to enthusiastically contribute to vertebrate ichnology. After briefly introducing the idea at the base of the Special Volume, as well as some aspects of the discipline and the current methodologies involved in ichnological studies, we present each of the contributions to serve the Italian ichnological heritage.

Keywords: tetrapods; ichnological record; Palaeozoic; Mesozoic; Quaternary; Italy; history of paleontology.

1. RATIONALE

150 years ago, Giulio Curioni (1796-1878) published the first scientific contribution on tetrapod ichnology based on material from Italy (Curioni, 1870). We felt that the thirtieth lustre represents an excellent opportunity to summarize the current state of the art on tetrapod ichnology in Italy, highlighting classic contributions as well as the numerous new studies conducted in recent years on the subject. The jubilee volume, entitled "*Tetrapod ichnology in Italy: the state of the art*", results from efforts of the scholars who first pioneered this discipline in Italy and of all the subsequent Authors, including those of the latest generations, who have joined working on the topic in recent decades.

After its introduction during the early 1950s by the Venetian Piero Leonardi, founder of the school of Geology of the Ferrara University, tetrapod ichnology in Italy has developed in several principal schools, starting with the 'School of Rome' during the seventies that was composed by Umberto Nicosia, Maria Alessandra Conti, Nino Mariotti and Giuseppe Leonardi of Sapienza University of Rome. The fruitful seeds thrown by these early Authors were collected by several generations of ichnologists, and despite the fragmented nature of the current academic system, which rewards mobility all around the world, we can say that these schools have come to this day and continue.

The main idea at the base of the volume was to propose a trans-generational approach. We firmly think, and we know it is a globally shared thought, that science represents a collective enterprise, and that we sit on the shoulders of giants, as already stressed and understood in the twelfth century by the French philosopher Bernard of Chartres. In total, 36 authors are involved and have actively collaborated in the drafting of this special volume, referable to at least six generations of ichnologists. The Journal of Mediterranean Earth Sciences immediately turned out to be the natural place to host the volume, considering that several of the first contributions highlighting the geological and paleobiogeographical importance of the Italian Mesozoic footprints have been published exactly in this Journal (under the former original name of 'Geologica Romana', founded in the Department of Earth Sciences of Sapienza University of Rome by prof. Bruno Accordi in 1962; see Romano and Nicosia, 2018).

The volume is composed of 10 contributions. Except for the present editorial and the historical note by Conti et al. (2020), each of the subsequent eight papers deals with the state of the art about the tetrapod ichnological record from Italy, namely from the Carboniferous (Marchetti et al., 2020a), Cisuralian (i.e. early Permian;

Santi et al., 2020), Lopingian (i.e. late Permian; Marchetti et al., 2020b), Triassic (Mietto et al., 2020), Jurassic (Petti et al., 2020a), Cretaceous (Petti et al., 2020b), Pleistocene (non-human footprints; Pillola et al., 2020), and Pleistocene and Holocene (human footprints; Avanzini et al., 2020). Each contribution illustrates all the ichnological sites, providing the interpretations proposed by the various Authors during the years concerning putative trackmakers and, when available, the possible biochronological and paleobiogeographical inferences (see below for further details). The Volume ends with the updated Italian general reference list (Antonelli et al., 2020), following the one published by D'Orazi Porchetti et al. (2008).

Although ichnology as independent field of study has been introduced relatively late in our country (see Conti et al., 2020), some of the first pioneers to deal with animal traces preserved in rocks and sediments should be sought exactly in the Italian panorama of the fifteenth century. First of all, as for many other fields of Earth Sciences *sensu lato* (De Lorenzo, 1920; Accordi, 1984; Vai, 1986, 1995, 2003a, 2003b, Romano, 2018a, 2018b; Coccioni, 2019), the genius of Leonardo da Vinci stands alone and giant in his time, and in the centuries to come. In the fortunate words of Rodolico (1963), Leonardo da Vinci represents the perfect Renaissance fusion of discovery at the same time aesthetic and scientific. Concerning ichnology, in Leonardo da Vinci we find the first ever illustration of *Paleodictyon* (Baucon, 2010), a hexagonal three-dimensional burrow system, one of the most common ichnofossil in the Neogene Apennine foredeep deposits. But we also find clear traces of tubular and elongated bioturbations in the wonderful painting "*The virgin of the rocks*" (Vai, 1995; Baucon, 2010) exhibited at the Louvre in Paris.

The demonstration that Leonardo da Vinci correctly interpreted and understood the geological processes and products, and then masterfully represented them in his paintings, is testified by the writings of the Tuscan genius. In this regard, Leonardo da Vinci wrote in sheet 10, recto of the Leicester Code: "*As in the strata, between one and other, there is still the route of earthworms, which walked between them, when* [the sediments] *were not yet dry*" ("*Come nelle falde, infra l'una e l'altra, si trova ancora li andamenti delli lombrici, che camminavano infra esse, quando non era ancora asciutta*").

It is evident from these words how the traces drawn in the paintings were not accidental, or a mere hyper-realistic representation of nature. Leonardo da Vinci had already understood the concept of sediment bioturbation by living organisms, and he explained these processes on canvases with an almost didactic attitude. Concepts that will be expressed with the same clarity only in the nineteenth century.

Last year marked 500 years since Leonardo da Vinci's death. Today, with our research and this Volume, we humbly carry on the furrow marked by the Italian genius over five centuries ago.

2. ICHNOLOGY: WHAT BONES DON'T SAY

Ichnology, from the Greek *ichnos* (trace) and *logos* (discourse), is that branch of geology and natural sciences *sensu lato* which deals with the study of the traces left by organisms both extant (i.e. 'neo-ichnology') and of the past (i.e. 'palaeo-ichnology'). In the context of vertebrate ichnology, the discipline obviously includes the study of footprints and trackways, but also the analysis of burrows, coprolites, eggs, nests and entire nesting sites.

When compared with other branches of palaeontology, and in particular with the classic studies of body fossils, ichnology is able to provide a 'vivid' and unique image of the organisms that have left their traces, with the possibility of making important inferences about the behaviour and various other elements of the biology and physiology of putative trackmakers; all elements and inferences often not obtainable from the sole anatomical study of bones.

Several aspects of extinct tetrapod general biology, including for example static and dynamic posture, locomotion, social behaviour, interspecific interactions, and related inferences about metabolism and general physiology, have been greatly improved and better understood thanks to ichnological studies (e.g. Thulborn and Wade, 1979; Farlow, 1981; Thulborn, 1981, 1982; Lockley, 1994; Avanzini, 1998; Lockley et al., 1998, 2003; Gierliński et al., 2009; Bernardi and Avanzini, 2011; Avanzini et al., 2012; Citton et al., 2012, 2018; Petti et al., 2014; Sacchi et al., 2014; Bernardi et al., 2015; Hatala et al., 2016; Romano et al., 2016a; 2019a; Romano and Citton, 2017; Lallensack et al., 2018; Reolid et al., 2018; Ahlberg, 2019; Bennett et al., 2019; Duveau et al., 2019; Lee et al., 2019; de Valais et al., 2020; Díaz-Martínez et al., 2020; Mujal and Schoch, 2020).

Taking the dinosaur clade as a paradigmatic example, also representing the bulk of the Italian Mesozoic ichnological record, from the seventies of the last century, first seminal studies published in leading journals began to use footprints to study locomotion and inferred speed in dinosaurs (e.g. Alexander, 1976; Farlow, 1981; Thulborn, 1981, 1982, 1984). These researches helped to eliminate the old concept of dinosaurs as slow and heavy lizards, providing a very different image which presupposed a much more active metabolism, more similar to that characterizing birds and mammals. In the following decades, several contribution have been published to analyse both bipedal and quadrupedal locomotion, identifying the average or maximum speed in several dinosaurs group and reconstructing the postures, type of locomotion and general structure (e.g. Dantas et al., 1994; Lockley et al., 1994a, 2002; Irby, 1996; Gatesy et al., 1999; Wilson and Carrano, 1999; Day et al., 2002; Henderson, 2003; Mossman et al., 2003; Wilson, 2005; Ezquerra et al., 2007; Wilson et al., 2009; Kim and Huh, 2010; Avanzini et al., 2012; Sellers et al., 2013; Bishop et al., 2017; Lallensack et al., 2018).

Evidences of parallel dinosaur trackways from several sites, depicting a consistent number of individuals of different sizes and ages moving in groups or 'herds', suggested a marked gregarious behaviour in different dinosaur clades (e.g. Bakker, 1968; Currie, 1983; Ostrom, 1985; Leonardi, 1989; Pittman and Gillette, 1989; Barnes and Lockley, 1994; Lockley et al., 1994b; Lockley, 1995; Matsukawa et al., 1997, 1999; Cotton et al., 1998; Day et al., 2004; Castanera et al., 2012; Lockley et al., 2012; Piñuela et al., 2016; Heredia et al., 2020). This interpretation seems to be indirectly reinforced by large shared nesting sites in some species (Horner and Makela, 1979; Horner, 1982, 2000; Sander et al., 2008; Reisz et al., 2012; Romano and Farlow, 2018).

Considering that the trace of the tail is extremely rare in the dinosaur traces record, the study of footprints highlighted how the tail was kept in such animals aligned, straight and raised from the ground, and not resting on the ground with a 'tripod' posture as found in many classic reconstructions of both bipedal and quadrupedal dinosaurs (see Romano et al., 2016b). Similarly, the study of elongated traces related to the metatarsal impression in both ornithopod and theropod dinosaurs allows to infer a really peculiar crouching behaviour, including both resting and locomotion phase that have been linked to both feeding posture, prey stalking or to simply walk very cautiously on waterlogged soft substrates (e.g. Lockley et al., 1998, 2003; Nicosia et al., 2007; Gierliński et al., 2009; Milner et al., 2009; Wilson et al., 2009; Citton et al., 2015a; Romano and Citton, 2017).

Still in the field of behaviour, Lockley et al. (2016) recently described physical evidence of substrate scraping by large theropods (largest scrapes up to 2 m in diameter) from several Cretaceous sites in Colorado. Scraping has been interpreted as a very interesting "display arenas" in the framework of "nest scrape display" behaviour, which characterizes several extant ground-nesting birds. The described scrapes thus indicate for the first time a clear evidence of stereotypical avian behaviour not yet proved for Cretaceous theropods, very likely connected to territorial activity close to nesting sites during the breeding season (Lockley et al., 2016; see also Hone, 2016; Kim et al., 2016; Lockley et al., 2018).

In the last decades tetrapod footprints have played a key role in palaeobiogeographic reconstructions. A paradigmatic example, extensively discussed in this Special Volume, is represented by the Italian panorama, were the discovery of several sites with dinosaur footprints leads to a consistent review of traditional geodynamic interpretations for the peri-Mediterranean Mesozoic carbonate platforms (Dalla Vecchia, 1994, 2001, 2003, 2008; Nicosia et al., 1999, 2007; Bosellini, 2002; Petti, 2006; Petti et al., 2008a, 2010; Sacchi et al., 2009; Zarcone et al., 2010; Citton et al., 2015b; Romano and Citton, 2017).

3. NEW APPROACHES AND FUTURE RESEARCH DIRECTIONS

In the last decade new methodologies coupled with advances in technological tools have allowed to develop new interesting approaches to tetrapod ichnology. A first interesting contribution is provided by the use of Principal Component Analysis and geometric morphometry in general for the study of both single footprints and entire trackways (e.g. Moratalla et al., 1988; Rodrigues and Santos, 2002; Tucker and Smith, 2004; Clark and Brett-Surman, 2008; Castanera et al., 2013, 2015; Romano and Citton, 2015, 2017; Lallensack et al., 2016, 2020; Buchwitz and Voigt, 2018; Costa-Pérez et al., 2019; Romano et al., 2019a). In fact, while PCA and geometric morphometry have been used for several decades for the study of the classic body fossils, their heuristic power has been applied only recently being in the study of the traces left by vertebrates. This approach allows to identify and highlight those characters most crucial for describing the shape of the footprints, also providing a useful indication of what the variability of the single portions of the footprints may be. This aspect can then be connected either to the trackmaker peculiar behaviour, functional prevalence in locomotion, or variability in the physical conditions of the substrate. The obtained results are useful to limit the fundamental characters to those related to the anatomy and locomotion of the trackmaker, rather than to variable boundary conditions. The method can have considerable ichnotaxonomic relevance, studying the variability or 'morphospace' occupied by a particular ichnogenus or ichnospecies, thereby allowing more quantitative decisions on the use of a more lumping or splitting approach. In particular cases, as the study of footprints referable to human groups, the method can be used to understand how many individuals left the footprints and therefore which was the social composition of clans in the Paleolithic (see Citton et al., 2017a; Avanzini et al., 2018; Romano et al., 2019a).

Another powerful, cheap, and fast-developing approach to ichnology is represented by photogrammetry, which despite being known for a long time, only recently has gone into the limelight thanks to a greater accessibility in terms of available digital technologies. This easily accessible technique allows to obtain high-definition 3D models starting from simple photos taken around the model, therefore with much lower costs than other techniques such as the laser scanner (Petti et al., 2008b; Falkingham, 2011; Cipriani et al., 2016; Romano et al., 2019b). The obtained 3D models make possible to observe the traces from all possible angles, and to study the differential depth of impression through cross sections and false colour images with contour lines. Footprint three-dimensional models can represent an objective form of communication and illustration of tetrapod traces, greatly complementing interpretations often linked to the knowledge and experience of the researcher. In parallel, the development of drone technology has allowed the first experimental 3D reconstruction of surfaces located in inaccessible or difficult to access sites, and to reconstruct large model of huge ichnosites (e.g. Citton et al., 2017b; Mazin et al., 2017; Romilio et al., 2017; Petti et al., 2018; Xing et al., 2018; Wiseman et al., 2020). Digital models are of central importance also for geoconservation, at least digitally preserving unique trampled surfaces, often subject to erosion and rapid deterioration linked to both human activities (e.g. caving) and natural processes, and for dissemination and evaluation of the geological (ichnological) heritage (e.g. Petti et al., 2008b, 2018; Cipriani et al., 2016; Romano et al., 2019b).

Another interesting approach is represented by actualistic (*sensu* Romano, 2015) studies of neo-ichnology, with extant tetrapods walking on different substrates or on baropodometric platform (e.g. Milàn, 2006; Milàn and Bromley, 2008; Genise et al., 2009; Jackson et al., 2009, 2010; Marty et al., 2009; Kubo, 2010; Milàn and Hedegaard, 2010; Schaller et al., 2011; Platt et al., 2012; Hasiotis and Hirmas, 2012; Bates et al., 2013; Curth et al., 2014; Falk et al., 2017; Gatesy and Falkingham, 2017; Pasenko, 2017; Farlow et al., 2018). These studies allow to analyse in detail the process of impression as well as the formation of the traces, with the great advantage of being able to control and to vary all the different variables and parameter for the experiments (e.g. type of substrate and sediments, substrate water content, substrate tilting, animal speed). These studies are also supported by new software and computer simulations, which allow for more quantitative modelling of the trace formation processes (e.g. Falkingham et al., 2009, 2011, 2014; Falkingham and Gatesy, 2014a, 2014b).

Finally, another promising approach regards the attempt to reconstruct the locomotion and particular biomechanics of the trackmakers starting from the differential depth of the footprints. In the last decades it has become clear that reducing the tetrapod footprints to a simple two-dimensional outline leads to the loss of a large number of useful information, both from an ichnotaxonomic point of view and for possible inferences on locomotion. Differently, considering the process of footprint formation as a dynamic process, with pioneers in this sense since the second half of the last century (e.g. Baird, 1957; Padian and Olsen, 1984; Thulborn and Wade, 1989; Thulborn, 1990), allows access to a much greater amount of information, regarding functionality, biomechanics, static or moving posture, interaction and registration of complex movements. Such approach, considering a footprint as a complex object developed in four dimensions as stressed clearly by Thulborn (1990, 2013), with a multiple and in continuum interaction between foot and substrate (e.g. Gatesy et al., 1999; Gatesy, 2003), has been accepted and used by several ichnologists to better understand the impression processes and to reconstruct locomotion and biomechanics in putative trackmakers (e.g. Farlow, 1992; Avanzini, 1998; Gatesy et al., 1999; Milàn et al., 2006; Sacchi et al., 2014; Citton et al., 2016, 2019; Romano et al., 2016a, 2020; Romano and Citton, 2017; Díaz-Martínez et al., 2018).

All these technologies and approaches are highly promising for the present and future of vertebrate ichnology both for reconstructing locomotion and biomechanics, and for identifying solid ichnotaxonomic characters. The specific osteological pattern of the axial skeleton, girdles, limbs and autopods, and the resulting differential functionalities in locomotion, have been irreversibly acquired by a particular tetrapod group through evolutionary processes, and in a unique node of the "bush of life". As already stresses by Carrano and Wilson (2001) and Romano et al. (2016a), the recognition of these phylogenetic characters mirrored in tetrapod footprints has as final goal the identification of 'natural' ichnotaxa or ichnotaxonomic units based on phylogeny and not on simple two-dimensional outlines, as found in the classic approach of the old typological philosophy of the last century.

4. SPECIAL VOLUME COMPOSITION

Contributions to this Special Volume cover almost the entire tetrapod ichnological record from Italy, by recapping all the studied ichnosites and synthesizing interpretations proposed by the Authors.

Conti et al. (2020) narrate the origins of Vertebrate Ichnology in Italy and the flourishing of different schools through the vicissitudes behind discoveries and trackers. The manuscript, which deliberately has the style of an anecdotal tale, consider the first hundred years of history of the discipline in Italy, introducing and discussing the development of methodologies and applications in the field of Earth Sciences and the striking contribution that tetrapod tracks provided, up to date, for regional and global reconstructions. By 'getting lost' in reading the paper, one might have the vivid feeling of Vertebrate Ichnology as a discipline 'in the flesh', and that the current, almost completely shared approach to the inherent epistemology takes root in the work of our pioneering colleagues. Well, one might say "The past is the key to the future".

Marchetti et al. (2020a) present the state of the art about the oldest tetrapod track record from Italy, described from the Pennsylvanian of Sardinia and Carnian Alps. The ichnoassociation is represented by anamniote tracks, and their occurrence is crucial for palaeocological and biochronological reconstructions.

Santi et al. (2020) report the current state of knowledge about the Cisuralian (i.e. early Permian) tetrapod track record. Since the first discoveries in the 19th Century, and particularly after a renaissance during the second half of the 20th century, Cisuralian footprints from northern Italy depicted an abundant, highly rich and diverse tetrapod ichnoassociation. The record also benefits of several geochronological constraints derived from radiometric dating of footprint-bearing units, thus playing a major role in the formulation of hypothesis about global evolutionary changes that took place in the late Palaeozoic.

Marchetti et al. (2020b) summarize the state of the art about the Lopingian tetrapod track record of Italy from the continental red beds of the Arenaria di Val Gardena formation-rank unit. The record comes from different localities of the Venetian Prealps and Carnian Alps, but especially (and historically) from the Bletterbach gorge in the Dolomites. The Lopingian ichnoassociation from northern Italy is, still to date, the most diverse and abundant known at global level. Since the systematic studies in the seventies and eighties of the 20th Century, which followed the seminal studies during the 19th Century and the pioneer work of Piero Leonardi (see Conti et al., 2020), the Permian record immediately turned out to be of remarkable significance for the understanding of evolutionary rates and changes in latest Palaeozoic tetrapods. A disruptive and detonating example was the recognition of the strong Triassic affinity of the ichnoassociation. It dates back to the systematic collection of tetrapod footprints started during the second half of the 20th Century and opened the way for all the future studies on late Permian ichnology in Italy, in addition to being the reference for ichnological studies abroad.

Mietto et al. (2020) begin with the discussion of the Mesozoic ichnological record, presenting the current state of knowledge about Triassic footprints. The bulk of the track-bearing localities belong to the Southern Alps domain, in addition to several ichnosites in Western and Maritime Alps, and Northern Apennines. In reporting the updated census, the Authors discuss major changes in the composition of the ichnofaunas, highlighting the shift from chirotheriid-dominated to dinosaur-dominated ichnoassociations triggered by the early Late Triassic global climate perturbation known as Carnian Pluvial Event.

Petti et al. (2020a) report the state of the art about Jurassic footprints from Italy. Except for the upper Pliensbachian Burano river ichnosite, where a trackway of a marine reptile was described from pelagic sediments, the Jurassic record is mostly represented by dinosaur footprints in marginal marine environments. Almost all of the ichnosites were found in Lower Jurassic deposits of Southern Alps and occur at different stratigraphic levels encompassing the Hettangian-Pliensbachian time interval. This record proved to be of great significance in the European ichnological panorama with regard to palaeonvironmental changes, paleogeography of the south Alpine sector and palaeobiology of trackmakers. As the manuscript title suggests, many young researchers trained with Early Jurassic footprints from different localities, orbiting around the well-known Lavini di Marco ichnosite, refining and deepening different methodologies (e.g. digital photogrammetry and laser scanning) that today can be considered a standard in ichnological investigations. The Jurassic record is also represented by the Mattinata ichnosite in Apulia (Southern Italy), which is provisionally assigned to the Kimmeridgian-Tithonian. The Apulian site provides important clues to the understanding of the palaeogeographic evolution of the peri-Adriatic sector during the Mesozoic.

The state of the art about the Cretaceous tetrapod track record is presented by **Petti et al (2020b)** that summarize the current knowledge and interpretations of twelve ichnosites scattered in Northern, Central and Southern Italy. The bulk of the record is reported from Aptian-Cenomanian carbonate platform deposits, to which are added few Lower Cretaceous sites and the mega-tracksite of Altamura (Upper Cretaceous), where thousands of dinosaur footprints occur. Also in this case the Cretaceous dinosaur track record, which is characterized by a high diversity of trackmakers, turned out to be dramatically significant for improve our understanding of the palaeogeographic and geodynamic evolution of the Mediterranean area during the late Mesozoic, binding new interpretations contrasting previous reconstructions.

Pillola et al. (2020) discuss the current knowledge about the non-hominid Pleistocene vertebrate record, which comes from two ichnosites in Sardinia and the well-known Foresta ichnosite in the Roccamonfina volcano (Campania). Even if 'scarce' in terms of abundance, this record appears characterized by a high producer diversity. The Authors analyse the record on the light of the huge amount of data regarding Pleistocene body-fossils, geology and biochronologic framework pointing to the palaeonvironmental reconstruction for the different ichnosites.

Avanzini et al. (2020) summarize the state of the art about the human track record of Pleistocene and Holocene ages, which recently takes advantage of new cutting edges methodologies. The Middle Pleistocene 'Devil's Trails' ichnosite from Foresta area (Roccamonfina volcano, Campania), constituting the oldest occurrence of human traces from Italy, is reported and discussed on the light of recent ichnological and archaeological findings. The Holocene record is constituted by the recently revised Upper Palaeolithic Grotta della Bàsura site (northern Italy), which contributed to improve our knowledge about individual and group level behaviour, social relationship and mode of exploration of a human group exploring a deep cave, and by the protohistoric sites of Afragola, Nola, Palma, Pompei (southern Italy) and Aosta (northern Italy). The contribution ends with the discussion of the ichnological findings reported from tunnel and trench floors of different military structures disseminated in Trentino Alto-Adige region (northern Italy) during the First World War.

5. CONCLUDING REMARKS

The first scientific contribution on tetrapod ichnology by Giulio Curioni, dated back to a century and a half ago, marks the beginning of this discipline in Italian academies, even if a deeper root in time is clearly testified already in the work of Leonardo da Vinci. Approximately from the mid-twentieth century, tetrapod ichnology began to sprout in Italy until the thriving growth of different schools, which are still very active, counting many ichnosites from the late Paleozoic to the Holocene to date tracked. The Special Volume we present covers the record of the ichnoassociations from Italy and it wants to be not a point of arrival, but a new starter line.

We hope that this volume will offer a trans-generational perspective to the researchers who are today engaged in wonderfully observing extinct animals in motion, and to those of tomorrow.

ACKNOWLEDGEMENTS - Umberto Nicosia and Maria Alessandra Conti are warmly thanked for introducing us to tetrapod ichnology. Special thanks to the Editor-in-Chief of Journal of Mediterranean Earth Sciences Salvatore Milli who immediately welcomed our proposal for the Special Volume, and has led and supported us in every phase of the realization. The technical editor Laura Di Pietro is thanked for support throughout the editorial process. A big thanks to all colleagues from all over the world who have given a great hand by improving the manuscripts or as reviewers of the submitted texts. In particular, we would like to thank Abdelouahed Lagnaoui, Andrea Villa, Angelo Cipriani, Bruce Rubidge, Carlos Neto De Carvalho, Christian Meyer, Diego Castanera, Eudald Mujal, Filippo Bertozzo, Giorgio Carnevale, Heitor Francischini, Ignacio Díaz Martínez, Ismar de Souza Carvalho, James Farlow, Joan Fornós, Martin Lockley, Michael Buchwitz, Neil Brocklehurst, Richard Cifelli and Spencer Lucas.

Last but not least, thanks to all the authors of different generations who have accepted to be part of this volume, providing their contributions to further underline the importance and long tradition of the Italian school of tetrapod ichnology. *Ad majora semper.*

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