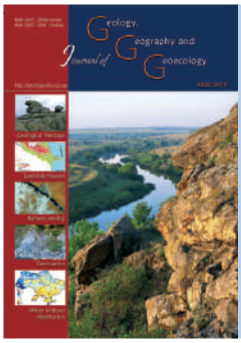

Journal of Geology, Geography and Geoecology

Journal home page: geology-dnu-dp.ua

ISSN 2617-2909 (print)
ISSN 2617-2119 (online)

Journ.Geol.Geograph.
Geology,
29(2), 252–257.
doi: 10.15421/112023

Detection of mineralogically accentuated biogenic structures with high-resolution geophysics: implications for ichnology and geoecology

Ilya V. Buynevich

Temple University, Philadelphia, USA, coast@temple.edu

Received: 19.04.2020
Received in revised form: 02.05.2020
Accepted: 10.05.2020

Abstract. Identification and mapping of small-scale physical and biogenic structures in sand has been a challenge to sedimentologists and ichnologists. Under natural conditions, biogenic activity (trampling tracks, burrows) alter primary sedimentary structures, but also serve as important paleoenvironmental indicators of geotechnical properties of sediments, omission surfaces, and ecosystem dynamics. Therefore, the ability to recognize such structures as anomalies in shallow subsurface, especially when using indirect non-invasive methods, such as geophysical imaging, is an important aspect of assessing their relative contribution to the overall erosional-depositional record. This study presents experimental evidence of the viability of two high-resolution geophysical methods in detecting sediment deformation that mimics shallow animal traces. High-frequency (800 MHz) ground-penetrating radar (GPR) imaging aided in visualizing a buried depression produced by a deer hoofprint cast indenter, with high-amplitude reflection return enhanced by a heavy-mineral concentration (HMC). Bulk *in situ* low-frequency (930 Hz), low-field magnetic susceptibility (MS) experiment supported the theoretical pattern of a decrease in MS over the thickest cover sand (maximum indentation depth) to ~0 mSI and the highest values over raised HMC horizon (marginal ridge; >8 mSI). Because both methods are affected by the presence and relative abundance of heavy minerals, the present approach can be applied in most siliciclastic settings. This study demonstrates the promise of extending the 2D visualization of subsurface targets to 3D datasets, with potential implications for sedimentological, ichnological, archaeological, and geoecological research that involves animal-sediment interaction at different scales.

Keywords: Georadar, magnetic susceptibility, heavy minerals, ichnology

Виявлення мінерально-акцентованих біогенних структур з використанням геофізичних методів високої роздільної здатності: наслідки для іхнології та геоекології

Ілля В. Буйнєвич

Темпльский університет, Філадельфія, США, coast@temple.edu

Анотація. Ідентифікація та відображення дрібномасштабних фізичних та біогенних структур у піску є викликом для седиментологів та іхнологів. У природних умовах біогенна активність (трамбування, сліди, нори) змінює первинні осадові структури, але також слугує важливими палеоекологічними показниками геотехнічних властивостей опадів, ерозійних поверхонь та динаміки екосистем. Тому здатність розпізнавати такі структури як аномалії в неглибоких шарах, особливо при використанні непрямих неінвазивних методів, таких як геофізична візуалізація, є важливим аспектом оцінки їх відносного внеску в загальний ерозійно-осадовий запис. У цьому дослідженні представлено експериментальні докази життєздатності двох геофізичних методів високої роздільної здатності при виявленні деформації осаду, що імітує неглибокі сліди тварин. Високочастотний (800 МГц) наземний георадар (GPR) дозволяє допомогти візуалізувати поховану западину, вироблену індектором відливу копита відбитків оленя, з віддачею відбиття з високою амплітудою, посиленим концентрацією важких мінералів (HMC). Експеримент з низькою частотною (930 Гц) низькопольовою магнітною сприйнятливістю (MC) підтримував теоретичну схему зменшення MC від ~ 0 mSI над покривним піском (максимальна глибина відступу) до найвищих значень над підштовхнутим HMC горизонтом (граничний хребет; > 8 mSI). Оскільки обидва способи впливають на наявність та відносне надходження важких мінералів, даний підхід може використовуватися в різних субстратах. Це дослідження демонструє перпсектививу розширити двовимірну візуалізацію підповерхневих цілей до 3D, з потенційними наслідками для седиментологічних, іхнологічних, археологічних та геоекологічних досліджень, що передбачає взаємодію тварин та опадів в різних масштабах.

Ключові слова: Георадар, магнітна сприйнятливість, важкі мінерали, іхнологія

Introduction. A wide suite of vertebrate and invertebrate organisms is responsible for generating billions of biogenic structures (surface traces and burrows) in both modern and ancient depositional settings (Vialov, 1966; Frey and Pemberton, 1986; Loope 1986; Fornós et al. 2002; Roberts 2003; Hasiotis et al., 2007; Lockley et al. 2007; Milàn et al. 2007a,b; Zonneveld, 2016). However, both preservation and detection of these structures, particularly in unconsolidated sandy substrates (= media) have been long considered to be challenging aspects in neo- and paleo-ichnological research (Loope, 1986; Allen, 1997; Fanelli et al., 2007; Buynevich, 2015). However many such traces rework the substrate, sometimes resulting in zoogeomorphic-scale impact (Laporte and Behrensmeyer, 1980; Butler, 1995; Scott et al., 2008). In recent decades, new applications of high-resolution geophysical techniques, such as ground-penetrating radar (GPR or georadar), have demonstrated success in rapid continuous imaging of shallow tracks and large burrows (Stott 1996; Buynevich, 2010; Buynevich, 2011b,c; Buynevich, 2012; Urban et al., 2019). The presence of mineralogical anomalies, such as heavy-mineral concentrations (HMCs), which consist of magnetite, ilmenite, garnet and other minerals denser than the background quartz and feldspar matrix often visually accentuates the traces in plan view and cross-section (Fig. 1; Van der Lingen and Andrews, 1969; Lewis and Titheridge, 1978). These anomalies also produce characteristic high-amplitude signal return in georadar images and can be detected using low-field magnetic susceptibility (MS) surveys (Buynevich, 2012). The latter is especially sensitive to ferrimagnetic (magnetite) content. Therefore, these techniques are potentially applicable to detecting near-surface biogenic structures accentuated by HMCs. This paper presents examples of laboratory experiments using an ungulate cast track indenter, with the aim of demonstrating the ability to detect the near-surface structure using high-resolution georadar imaging and magnetic susceptibility trends.

Materials and methods. The laboratory experiment consisted of two separate stages (GPR and MS survey techniques) that simulate natural conditions (Table 1; Fig. 2). For georadar imaging (Fig. 2B), a quartz-rich sand surface (10-cm-thick layer in a plastic box) was imprinted with a cast of a white-tailed deer (*Odocoileus virginianus*) hoofprint (length = 7 cm; maximum width: 4 cm) to a depth of ~1-2 cm (heel-to-toe) to simulate traces observed in natural settings (Fig. 1B). The imprint produced slight marginal ridges (MR) or expulsion rims (Fig. 2A, Part 1). The entire track surface was then covered by a thin (1-2 mm) layer of mixed almandine garnet and magnetite heavy-mineral concentration (Fig. 2A, Part 2; Fig. 3A). Subsequently, this surface was capped by a layer of quartzose sand to a depth of 1-2 cm in order to bury the track (Fig. 2A, Part 3; Fig. 3B). A survey transect was collected along the central longitudinal path of the track

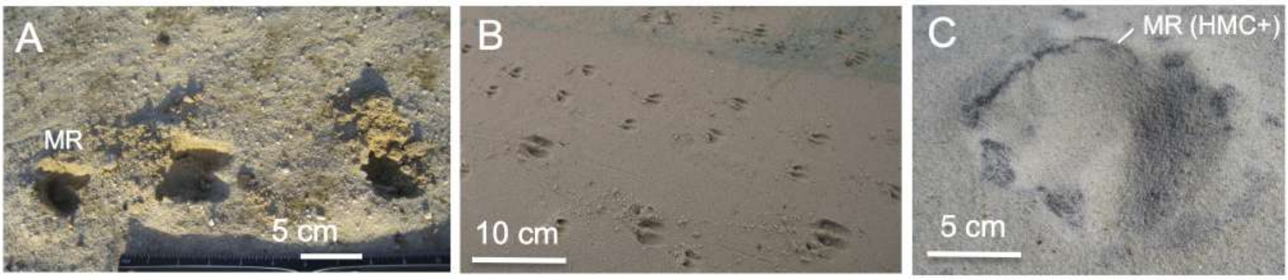

Fig. 1. Examples of ungulate tracks in sand: A) Deer hoofprints in coarse fluvial sand (Delaware River, Pennsylvania, USA; MR – marginal ridge); B) Large and small ungulate tracks (deer, boar) on a lagoon shoreline, with slight heavy-mineral (almandine) enrichment (Curonian Lagoon, Lithuania); C) Feral horse footprint in coastal dune sand, with heavy-mineral concentration (HMC+) composed of magnetite along the marginal ridge (Assateague Island, Maryland, USA)

Table 1. Flowchart of experimental design of GPR and MS experiments

Stage	Georadar (GPR)	Magnetic Susceptibility (MS)	Example (Figure)
Imprinting	Track cast indent into 10 cm sand bed	Track cast and sensor indents	2A(1), 4A
Accentuation	Garnet-magnetite mix (1-2 mm HMC)	Garnet-magnetite mix (1-2 mm HMC) Random MS sensing of HMC	2A(2), 3A, 4B
Burial	1 cm of quartz sand (more over indent)	2 mm of quartz sand (more over indent)	2A(3), 3B
Imaging	800 MHz monostatic antenna profile	MS2K field sensor profile	2B, 2D, 3C, 4C

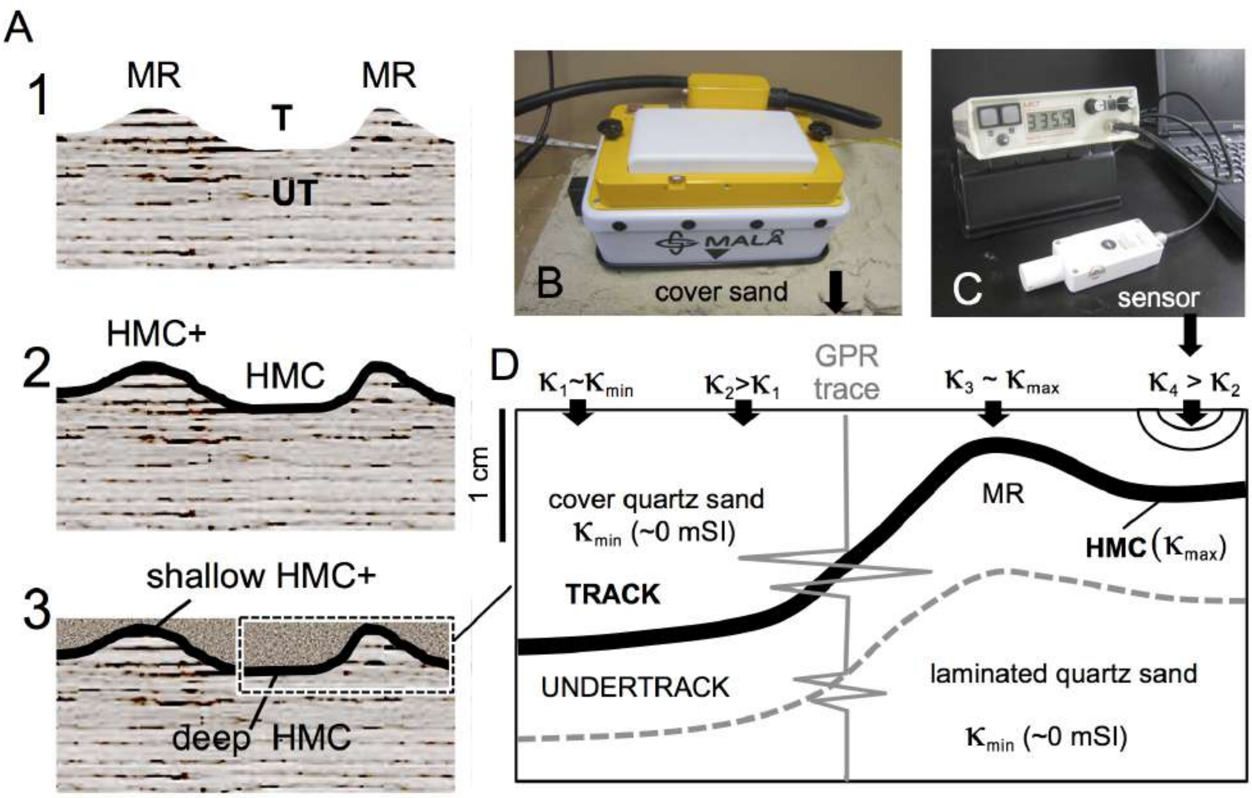

Fig. 2. A) A conceptual sequence of a buried tracking surface with a mineralogical anomaly: (1) track (T) emplacement and marginal-ridge (MR) formation on a sand surface with minor heavy-mineral content (UT – undertracks), (2) heavy-mineral concentration (HMC) formation due to aeolian action (HMC+ - enhanced enrichment over MR), and (3) burial of the accentuated track by quartz-rich cover sand. B) a monostatic 800 MHz GPR antenna over a cover sand; C) Bartington low-field magnetic susceptibility (MS) control unit with an MS2K sensor; D) idealized cross-section of a buried track (see location in A3). Oscilloscope shows higher magnitude electromagnetic georadar response to HMC. Bulk MS values (κ) are shown for different media and expected surface result (see Table 1 for experimental flowchart)

using a digital MALÅ Geoscience radar system with a monostatic 800 MHz antenna (Fig. 2B). The resulting radargram was not post-processed due to lack of surface topography and the need for detection of small-scale subsurface sediment deformation (for application GPR technique in neo-ichnological research see Buynevich, 2011a). The heavy mineral layer was used to accentuate the electromagnetic radar signal response (Fig. 2D).

In a second experiment, the *in situ* low-field magnetic susceptibility surveys, a Bartington MS meter with an MS2K field sensor (930 Hz; Fig. 2C) was used. Similar to georadar setup, a track cast (Fig. 4A) was imprinted into a quartz sand surface with low bulk susceptibility (κ ~0 mSI; Fig. 2D). In addition, a shallow (2-3 mm) imprint was produced by pushing the 2.5-cm-wide sensor into the sand behind the hoofprint, thereby simulating a small trace or an upper part of a burrow shaft (Table 1; Fig. 4B). The detection sensitivity of the sensor is a 50% signal decay at a depth of 0.3 cm. Several random measurements of heavy mineral layer were taken prior to burial. Conceptually, due to variations in the thickness of cover sediment over the HMC-accentuated tracking surface, it is expected that the bulk susceptibility will range from near-minimum background over deepest parts of the indented features to near-maximum over shallow elements, such as marginal ridge (Fig. 2D).

Results and Discussion. The results of this study show success of both near-surface geophysical methods in detecting sediment deformation. Indenter mechanics. The impression of a track cast is manifested as a downward-dipping reflection in the GPR image (Fig. 3D), consistent with high-amplitude response of a heavy-mineral lamina (as indicated in Fig. 2D). The mechanical deformation is typical for that of an indenter, with the likely formation of undertracks (Allen, 1989; Allen, 1997; Milàn and Bromley, 2006.). These are likely expressed by truncated sediment layers below the main hoofprint image, at a depth of at least 4 cm (Fig. 3D). Therefore, even an 800 MHz frequency is sufficient to detect the buried feature, with even better results expect for higher-frequency setups. It is important to note that detection, rather than vertical resolution, was the focus of this study. The latter is limited by incoming electromagnetic pulse frequency

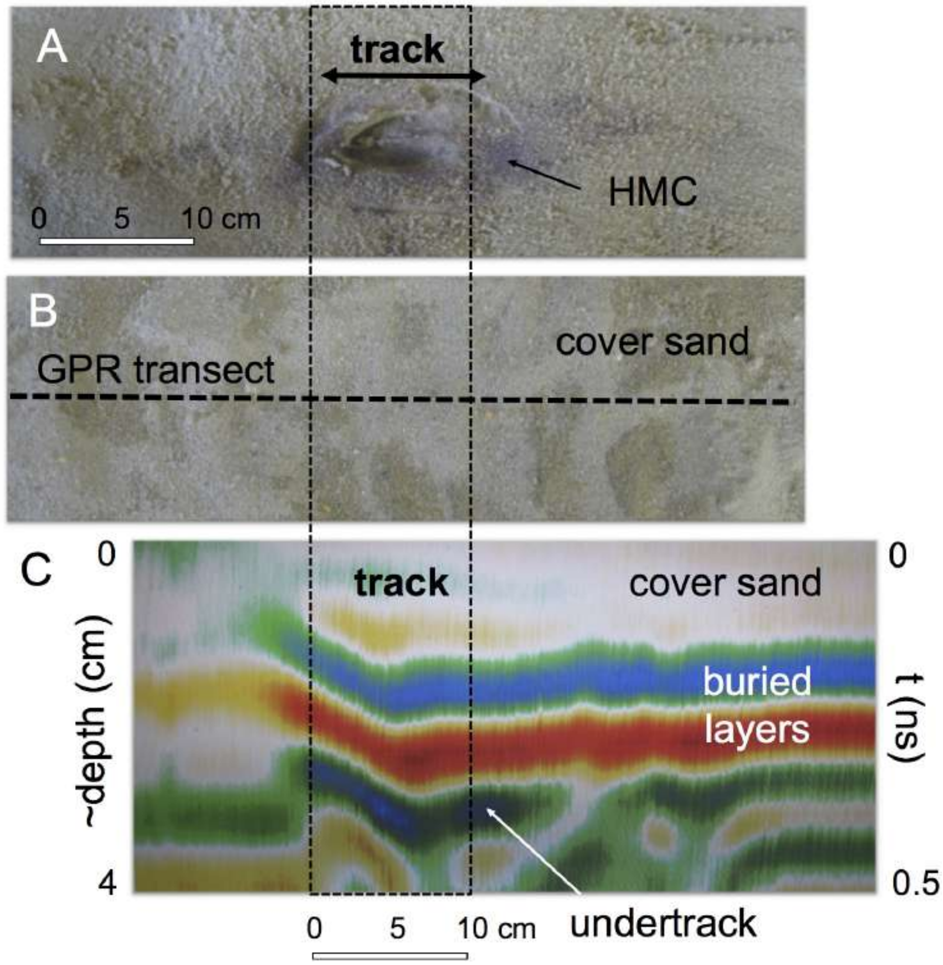

Fig. 3. Georadar imaging of a buried track: A) hoofprint cast emplaced into a laboratory sand and covered by a thin heavy-mineral concentration (HMC); B) surface of cover sand with a GPR antenna survey line; C) Radargram (800 MHz) showing the downward-dipping reflections at the buried track location, with undertrack(s) below. The unaffected sediment layers are at right, with a relatively low-amplitude signature of the overlying cover sand (t – two-way travel time in nanoseconds (10^{-9} s), using $v \sim 15$ cm/ns)

and is the ability to discriminate between multiple overlying targets (e.g., two or more closely spaced horizons, top and bottom of a point-source anomaly; Buynevich et al., 2014). The difference in signal amplitude between HMC (strong) and overlying cover sand (weak) is also expressed in the radargram, to the right of the imprint (Fig. 3D).

The bulk magnetic susceptibility experiment was similarly successful in revealing the two indented structures (hoofprint cast and sensor imprint; Fig. 4). Several random pre-burial HMC measurements yielded values between κ = 4.66-9.92 mSI (triangles in Fig. 4C). Following burial by diamagnetic (low to negative MS) quartz sand, the pattern of MS values clearly show broad depression associated with the footprint (0.008 mSI) and a narrow dip (0.025 mSI) at the location of the sensor indent. Bulk MS readings greater than the mean of κ = 3.3-3.5 mSI, are associated with the relatively undisturbed parts of the profile, with the highest value of κ = 8.23 just behind the footprint (Fig. 4C). This anomaly is located at the point of a relatively low pre-burial HMC concentration and is interpreted as a marginal ridge (MR) produced during cast emplacement (Figs. 1C; 2A; 2D).

In summary, the findings of this study demonstrate the viability of both GPR imaging and MS surveys can be used to detect and visualize shallow subsurface sedimentary structures similar to those generated by animals. Recognition and mapping will be improved by collection of closely spaced GPR transects and MS profiles to generate pseudo-3D and true 3D images of biogenic structures. Whereas the latter depends heavily on the presence of ferrimagnetic (e.g., magnetite) and paramagnetic minerals, georadar pulse responds to fabric-related water retention and other fine-scale properties, as indicated by successful footprint imaging in carbonate and evaporate settings (Buynevich et al., 2014; Urban et al., 2019). In addition to neo- and paleo-ichnological applications, this research can also aid in geoecological assessment of animal-landscape interaction and conservation of important footprint sites (Loope, 1986; Zonneveld, 2016). Future experiments must therefore include a spectrum of substrate lithologies in both field

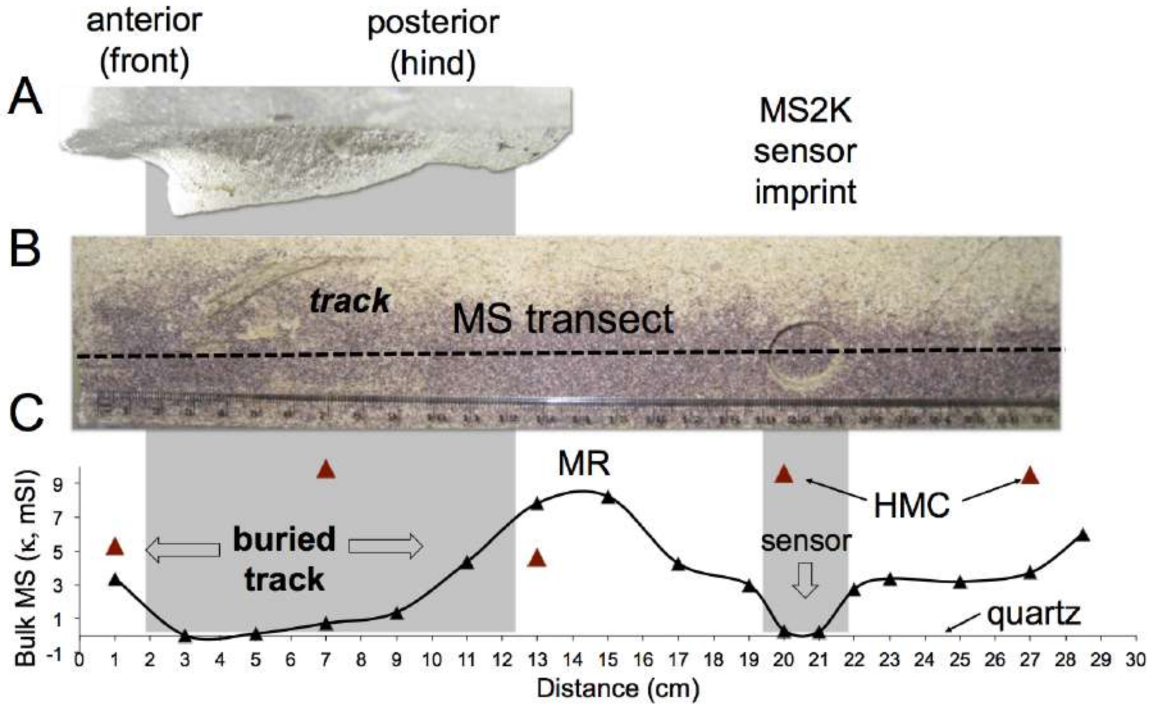

Fig. 4. Low-field magnetic susceptibility (MS) transect: A) hoofprint cast; B) track (at left) and MS2K sensor (at right) imprints into laboratory sand covered by a thin heavy-mineral concentration (dashed line shows the MS sampling transect); B) surface of cover sand with a GPR antenna survey line; C) MS values (2 cm interval) of sediment surface following burial by quartz-rich cover sand (triangles show random point measurements of HMC prior to burial). Note the low values below the two imprints and a peak likely related to the marginal ridge

and laboratory settings, with the ultimate goal of assembling diagnostic criteria for distinguishing physical and biogenic structures.

Acknowledgments

This research was funded by the National Geographic Society CRE Grant #8060-06 and the College of Science and Technology, Temple University. The author thanks Christopher Seminack, Zachary Grimes, Donatas Pupienis, Albertas Bitinas, and Aldona Damušytė for assistance in the field and Justin Darrow for help with laboratory experiments.

References

Allen, J. R. L., 1989. Fossil vertebrate tracks and indenter mechanics. Journal of the Geological Society, London, 146, 600-602.

Allen, J.R.L., 1997. Subfossil mammalian tracks (Flandrian) in the Severn Estuary, S.W. Britain: mechanics of formation, preservation and distribution. Philos. Trans. R. Soc. Lond., B 352, 481-518.

Butler, D.R., 1995. Zoogeomorphology – Animals as geomorphic agents. Cambridge University Press, Cambridge, 240 p.

Buynevich, I.V., 2011a. Buried tracks: ichnological applications of high-frequency georadar. Ichnos, 18, 189-191.

Buynevich, I.V., 2011b . Heavy minerals add weight to neoichnological research. Palaios, 26, 1-3.

Buynevich, I.V., Darrow, J.S., Grimes, Z.T.A, Seminack, C.T., Griffis N., 2011. Ungulate tracks in coastal sands: recognition and sedimentological significance. Journal of Coastal Research, SI 64, 334-338.

Buynevich, I.V., 2012. Morphologically induced density lag formation on bedforms and biogenic structures in aeolian sands. Aeolian Research, 4, 1-5.

Buynevich, I.V., 2015. Recent vertebrate tracks in sandy substrates and their paleoenvironmental implications: examples from coastal Lithuania. Baltica, 28, 29-40.

Buynevich, I.V., Curran, H.A., Wiest, L.A., Bentley, A.P.K., Kadurin, S.V., Seminack, C.T., Savarese, M., Bustos, D., Glumac, B., Losev, I.A., 2014. Near-surface imaging (GPR) of biogenic structures in siliciclastic, carbonate, and gypsum dunes. In Hembree, D.I., Platt, B.F., and Smith, J.J., (eds.), Experimental Approaches to Understanding Fossil Organisms: Lessons from the Living, Springer, Dordrecht, The Netherlands, pp. 405-418.

Fanelli, F., Palombo, M.R., Pillola, G.L., and Ibba, A., Tracks and trackways of *"Praemegaceros" cazioti* (Depéret, 1897) (Artiodactyla, Cervidae) in Pleistocene coastal deposits from Sardinia (Western Mediterranean, Italy). Bollettino della Società Paleontologica Italiana, 46, 47-54.

Fornós J.J., Bromley, R.G., Clemmensen, L.A., Rodriguez-

Perea A., 2002. Tracks and trackways of *Myotragus balearicus* Bate (Artiodactyla, Caprinae) in Pleistocene aeolianites from Mallorca (Balearic Islands, Western Mediterranean). Palaeogeography, Palaeoclimatology, Palaeoecology, 180, 277-313.

Frey, R.W., Pemberton, S.G., 1986. Vertebrate Lebensspuren in intertidal and supratidal environments, Holocene barrier islands, Georgia: Senckenbergiana Maritima, 18, 45-99.

Hasiotis, S.T., Platt, B.F., Hembree, D.I., Everhart, M., 2007. The trace-fossil record of vertebrates. In: Miller, W., III (ed.) Trace fossils-concepts, problems, prospects. Elsevier Press, pp. 196-218.

Laporte, L.F., Behrensmeyer, A.K., 1980. Tracks and substrate reworking by terrestrial vertebrates in Quaternary sediments of Kenya. Journal of Sedimentary Petrology, 50, 1337-1346.

Lewis, D.W., Titheridge, G., 1978. Small scale sedimentary structures resulting from foot impressions in dune sands. Journal of Sedimentary Petrology, 48, 835-838.

Loope, D.B., 1986. Recognizing and utilizing vertebrate tracks in cross section, Cenozoic hoofprints from Nebraska. Palaios 1, 141-151.

Milàn, J., Bromley, R.G., 2006. True tracks, undertracks and eroded tracks: experimental work with tetrapod tracks in laboratory and field. Palaeogeography, Palaeoclimatology, Palaeoecology, 231, 253-264.

Milàn, J., Clemmensen, L.B., Buchardt, B., Noe-Nygaar, N., 2007a. A late Holocene tracksite in the Lodbjerg dune system, northwest Jylland, Denmark. In: Lucas, S.G., Spielman, J.A., Lockley, M. (eds.) Cenozoic vertebrate tracks and traces, vol 42. New Mexico Museum of Natural History and Science, Albuquerque, pp. 241-250.

Milàn, J., Bromley, R.G., Titschack, J., Theodorou, G., 2007b. A diverse vertebrate ichnofauna from a Quaternary eolian oolite from Rhodes, Greece. SEPM Special Publications, 88, 333-343.

Scott, J.J., Renaut, R.W., Owen, R.B., 2008. Preservation and paleoenvironmental significance of a footprinted surface on the Sandai Plain, Lake Bogoria, Kenya Rift Valley. Ichnos, 15, 208-231.

Stott, P., 1996. Ground-penetrating radar: a technique for investigating the burrow structure of fossorial vertebrates. Wildlife Research, 22, 519-530.

Urban, T.M., Bennett, M.R., Bustos, D., Manning, S.W., Reynolds, S.C., Belvedere, M., Odess, D., Santucci, V.L., 2019. 3-D radar imaging unlocks the untapped behavioral and biomechanical archive of Pleistocene ghost tracks. Scientific Reports, 9, 16470.

Van der Lingen, G.J. and Andrews, P.B. 1969, Hoof-print structures in beach sand: Journal of Sedimentary Petrology, 39, 350-357.

Vialov, O. S., 1966. Sledy Zhiznedeyatelnosti Organizmov i Ikh Paleontologicheskoe Znachenie. [Traces of the Vital Activity of Organisms and their Paleontological Significance]. Kiev, Naukova Dumka, Academy of Sciences, Ukrainian S.S.R., 219 pp. [in Russian].

Zonneveld, J.-P., 2016. Applications of experimental neoichnology to paleobiological and evolutionary problems. Palaios, 31, 275-279.