Matthew R. Bennett · Sarita A. Morse

Human Footprints: Fossilised Locomotion?

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For
Fredrick George Lawley (1916–1991)
Alvina Morse (1909–2008)

Preface

There is something evocative in a human track. It helps one form an instant connection with the track-maker and their journey, blending past with present. Their preservation is in itself a rare occurrence in the geological record and they contain information not only about human presence, but about the track-makers themselves, as well as the way in which they moved across the landscape providing evidence of fossilised locomotion. There is a personal connection here as well. I come from a line of geographers on my paternal side and I first worked in Scotland and the Arctic on questions of glacial geology. But my maternal Granddad – a wonderful man, who sadly is no longer of this world – was a chiropodist, or as they like to be called these days a podiatrist. So for me the study of human tracks represents a convergence in my own ancestry, one that also reflects the interdisciplinary convergence of geology with the subjects of archaeology, anthropology and podiatry needed for their study.

This is a book about human tracks, not only their occurrence around the world, but also what can be learned from them, and it aims to equip the reader with the tools to enable their study whether it be for the sheer pleasure of enquiry, in the pursuit of scientific questions in such fields as geoarchaeology and palaeoanthropology, or in the pursuit of criminals as forensic scientists. The book has been written by me as first author, but with an essential and invaluable contribution from Sarita A. Morse who while at the University of Liverpool acquired, processed and analysed much of the data described here.

Bournemouth, UK Matthew R. Bennett
April 2014

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Many people have provided us with access to specimens and field sites, as well as company and hard work in the field, including: Francis Thackeray, Cynthia Liutkus-Pierce, Kevin Cole, David Roberts, Gordon Roberts, Sally Reynolds, Harry Manley, David Huddart, Silvia Gonzalez, Melanie Crisfield, Dominic Strafford, Matteo Belvedere, Lisa Santello, Peter Falkingham, Gustavo Politis, Cristina Bayon, Teresa Manera and Ricardo Melchor. We would like to acknowledge the support of the Koobi Fora Field School (2007–2009) and the contribution to our research of Jack Harris, Kay Behrensmeyer, Emma Mbua, Purity Kiura and Jack McCoy as well as the numerous students of the Field School. Thanks are due to the National Museums of Kenya for allowing access to Laetoli casts in 2008, to the Iziko South African Museum in Cape Town for providing access to the Langebaan tracks and to the East London Museum (South Africa) and in particular its curator Kevin Cole, an inspiring and visionary individual, for access to the Nahoon tracks. We would like to thank Fanie Du Preez of Kuiseb Delta Adventures and Chris Lourens of the Free Air Guest House (Walvis Bay) for access and logistical support with respect to the Namibian footprints. Charlene Steele processed much of the raw field data from Namibia. The wonderful Daniel Marty offered us a range of footprint and dinosaur photographs and Cynthia Liutkus-Pierce provided information on the Engare Sero tracks in Tanzania. Former Bournemouth students Paulley, Butters, Strugnell, Perkins and Wollf are thanked for the data on track morphology and walking speed cited in Sect. 6.4. SAM would like to acknowledge her husband, family and friends for their continuous support, with special thanks to Robin Crompton for his advice and supervision. MRB would like to acknowledge the on-going support of Bournemouth University and the contribution made by Marie Dunning, Rebecca Dolling and Kathryn Hill, as well as the support and patience of his family, whose footprints feature at various points throughout the book; the challenge now is for them to find their tracks!

Contents

Chapter 1
Fossilised Locomotion

Abstract In this first chapter we provide a broad overview of human trace fossils (ichnology) and outline the contents of and rationale for this book. The potential for human tracks to tell us about how our ancestors may have walked is discussed as is the contribution that human tracks can make in other areas of archaeology and forensic science. Key definitions are introduced, as is a simple model of human track formation.

1.1 Human Tracks

Watch couples dance or children play and you will see the foot in action; an amazing machine. Just 26 bones sheathed in skin and sinew, with muscles that can propel you forward, backwards, up and down, allowing you to twist, turn, balance and control your speed with precision. Yet despite over a hundred years of research (Morton 1935) our understanding of the human foot remains rudimentary and knowledge of how our ancient ancestors walked a subject of conjecture and debate.

Within the geological record human and animal tracks occur infrequently; freak occurrences of sedimentary preservation, with each one holding a rare glimpse of locomotive behaviour (Fig. 1.1). Currently the oldest and most famous hominin tracks are those at Laetoli in Tanzania made some 3.66 Ma ago, preserved in volcanic ash and probably made by *Australopithecus afarensis* (Agnew and Demas 1998; Deino 2011; Leakey and Harris 1987; Leakey and Hay 1979; White and Suwa 1987). In 2009 details of a track site close to the village of Ileret in northern Kenya were published as the second oldest hominin footprint site, dating to 1.5 Ma ago (Bennett et al. 2009). These footprints are believed to have been made by *Homo erectus* (Dingwall et al. 2013), one of the first species of hominin capable of long-distance walking and running. Comparison of the Ileret and Laetoli tracks has the potential therefore to explore the transition in locomotive style between the genera of *Australopithecus* and *Homo* (Raichlen et al. 2010; Crompton et al. 2012). The development of bipedalism was a critical stage in human evolution, as was the later transition from early habitual bipeds such as *Australopithecus afarensis* made famous by the skeleton 'Lucy' to endurance walkers and runners which characterise more modern humans such as *Homo erectus* and ourselves *Homo sapiens* (Bramble and Lieberman 2004). The ability of our ancestors to walk efficiently will have influenced their interaction with the

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Fig. 1.1 Modern human track made by a habitually unshod individual in fine-grained sand/silt in a dry river bed in northern Kenya. Note the: track cross-cuts ripples with heavy mineral concentrations in the troughs and the compression of these minerals in the floor of the track; rim structure formed by the up-fold of the surface laminated sands; and desiccations cracks formed after the track was made

landscape: the way they foraged and hunted for food, gathered raw materials to use as tools and their ability to migrate across the globe.

Fossil foot bones of early hominins are rarely found in association with the skeletons of known hominin species and the fossil record is fragmentary. Small bones of the foot scatter easily once released from the soft-tissue that surrounds them and consequently they are poorly preserved in the geological record prior to the advent of burial practices. But in truth fossil foot bones alone rarely give an unambiguous indication of the way our early ancestors walked, since the bones of the foot act through a series of complicated soft tissues which are not preserved. Human tracks provide an alternative source of evidence about our ancestor's feet, formed as they walked across soft-ground leaving a record of 'fossilised locomotion.' The critical question is how do tracks record the forces applied to the ground by a track-maker and what can these forces tell us about the way in which they walked? As the foot meets the ground it interacts with the substrate to leave a track which involves the convergence of biomechanics and geology.

There is also an ever growing number of human track sites discovered around the world from more recent times made by *Homo sapiens* found in such diverse settings as coastal mudflats, caves and imprinted in layers of volcanic ash (Allen 1997; Avanzini et al. 2008; Lockley et al. 2008). These sites are not only of archaeological importance in themselves, since they provide information on human presence and allow inferences about the track-makers to be made such as their stature, but they also provide reference material with which to help decipher the record of fossilised locomotion preserved within more ancient tracks. While some of these tracks are preserved in lithified, or partially lithified, volcanic ash such as the tracks on Jeju Island (South Korea), or those at Acahualinca in Nicaragua (Kim et al. 2009; Schmincke et al. 2009, 2010), most are preserved in unlithified, fine-grained silt and fine sand and in some notable cases prints are exposed by coastal erosion and then destroyed (e.g., Aldhouse-Green et al. 1993; Roberts et al. 1996). The conservation of these soft-sediment tracksites, especially when dealing with sites of palaeoanthropological significance like those at Ileret is challenging (Bennett et al. 2013). Human tracks are not only of relevance to archaeology and palaeoanthropology however since footwear evidence can in some cases be vital to criminal investigations, the proverbial 'footprint in the flower bed' (Robbins 1985; Bodziak 2000). Here geoarchaeology converges with modern forensic science with both parties having the opportunity to learn from one another.

In light of the above the aims of this volume are therefore varied and we identify four main goals: (1) to draw together in one place, a diverse literature for those interested in human tracks whether they be geologists, archaeologists, palaeoanthropologists or forensic scientists; (2) to provide a review of modern methods of data collection and analysis; (3) to explore the role and influence of substrate on track formation and preservation; and (4) to clearly state what can and cannot be inferred from human tracks. The structure of the book follows these four broad aims, but first we need to clarify some key issues of nomenclature and orientate ourselves with respect to the human foot. We recognise that those reading the book are likely to have different academic backgrounds and have therefore included a glossary located at the end of the book to aid the reader navigate any specialist terms with which they are not familiar.

1.2 Key Concepts and Definitions

Fossil footprints whether made by humans or other animals are examples of trace fossils and the technical term for a trace fossil is an ichnofossil. The study of trace fossils is therefore the study of ichnology derived from the Greek 'ikhnos' meaning track or trace. Current convention mainly derived from the study of dinosaur traces is to refer to individual footprints as tracks and a linked sequence of tracks (i.e. footsteps) as a trackway, while the track-maker is the individual who left the tracks (Table 1.1). A single, spatially-restricted track-bearing horizon is referred to as an ichnoassemblage, which becomes an ichnocoenosis if it is recurrent and an ichnofacies when it can be linked to specific sediments and environments (Hunt and Lucas 2007). There is a complex and formal taxonomic methodology for defining ichnofossils particularly where the linkage to an extant track-maker is not clear (Donovan 1994). While the formal use of ichnotaxa has been adopted recently by a

Table 1.1 Commonly used terms with respect to tracks following Marty et al. (2009)

Term	Definition
Track	A single footprint or partial impression made by the foot of an animal
True track	A track whose lower surface was in contact with the plantar surface of the track-maker's foot
Under track	A track that is formed by the compression of sediment below the track-maker's foot. When exhumed an under track may be visible but its surface will not have been directly in contact with the track-maker's foot, if for example the original contact surface has eroded. Thulborn (2012) use the term 'transmitted relief' to describe an under track which describes the situation well, but has not been widely adopted
Elite track	A well-preserved true track (Lockley and Hunt 1995; Lockley and Meyer 2000)
Trackway	A series of tracks made by the same animal (Leonardi 1987; Thulborn 1990; Marty et al. 2009)
Track-maker	The animal that made the track
Tracked surface	The surface or palaeosurface on which the track-maker walked/moved (Fornós et al. 2002)
Overall track	If the track walls – sides of a print – are not vertical then the outer track dimension (overall track) will be larger than the dimension of the track-maker's foot or the track bottom (true track; Brown 1999)
Internal overtrack	Forms by covering of the track bottom (true track) without covering the entire overall track. Often associated with the trapping of sediment within microbial mats formed in the wet print interiors (Marty et al. 2009)
Natural track cast	A mould of a track formed by infilling sediment forming a negative replica (Lockley 1991)
Overprinting	Caused by the track-maker or another animal overprinting an original track
Displacement rim	A marginal rim of a track formed by the displacement of sediment, sometimes referred to as a 'push-up' structure or a bourrelet (Allen 1997; Manning 2004)
Track ejecta	Material ejected by the removal of the track-maker's foot from a track; may be thrown forward by the track-maker's toes (Allen 1997)

few authors (Kim et al. 2008; Meldrum et al. 2011) it is not a methodology that has been widely applied to human tracksites and is not an approach that is favoured here.

At this point we need to recognise that there are different types of track and we identify three basic types:

1. Two-dimensional tracks which record the outline and surface texture of a foot; for example if one was to walk barefoot in a tray of paint one would leave a series of two-dimensional tracks until the paint adhering to the foot was removed. These types of tracks are common at some types of crime scene where a suspect or victim may leave a trail of bloody tracks for example.
2. Three-dimensional tracks which record the outline and the depth of an impression made by a foot walking on a deformable substrate. The simplest example is to think of the tracks one might make at the beach. These are the tracks which are discussed for the most part in this volume.

3. Pressure-tracks which record the outline and the contact pressure through time as a foot makes contact with the ground. There are various types of plantar force plates and pressure sensitive walkways and treadmills that record the contact pressure in various ways (e.g., peak, average, cumulative) and across different areas of the foot through time as it first strikes, makes contact with and then finally pushing off the ground. This type of information is used extensively in biomechanical and clinical studies and plantar pressure should correlate in some way with the depth of a track which in theory represents a time integrated strain response to the applied pressure.

In navigating a human track we refer to areas that reflect the portion of the foot that made it using common biological directional terms. Therefore the heel is called the proximal portion and the forefoot is the distal portion. The outside edge is referred to as the as the lateral side and conversely the inside edge is the medial side (Fig. 1.2a). The plantar surface is the bottom (sole) of the foot and the upper (superior) surface is the dorsal surface and to be consistent with this the base of a track is therefore referred to here as the plantar surface. The sides above (superior to) the plantar surface are called the track walls (Table 1.1). We describe the big toe as the first toe, also commonly referred to as the hallux. We use the word adduction to describe the situation where the first toe is in line with the longitudinal axis of the foot and abduction to describe the situation where the first toe is displaced medially. The medial longitudinal arch refers to the inside arch of the foot (i.e., parallel to the sagittal plane) and its perpendicular as the transverse arch (i.e. running from the lateral to medial side), which follows the coronal plane. We use the term 'ball' to refer to the area proximal of the toe pads beneath the metatarsal heads and distal of the midfoot defined by the areas occupied by the medial longitudinal arch if present.

Movements of the foot in making a track are referred to by a range of terms, including: (1) dorsiflexion, the movement of the foot upwards by flexing the toes; (2) plantarflexion, the movement of the foot vertically downwards by extending the toes; (3) supination as a tendency for someone to walk on the outside/lateral edge of their foot; (4) pronation as the tendency for someone to walk on the inside/medial edge of the foot; (5) eversion as a tendency for the sole of the foot to move away from the medial/sagittal plane; and (6) inversion as a tendency for the sole of the foot to move toward the medial/sagittal plane. A wide variety of definitions and procedures are used in the literature to define the basic linear dimensions of the foot and these are reviewed in Sect. 2.6.

1.3 Models of Track Formation

Figure 1.2b summarises some of the key variables which need to be considered in the formation of a human track. There is an application of a force termed plantar pressure, via the foot as it makes contact with the ground which leads to the

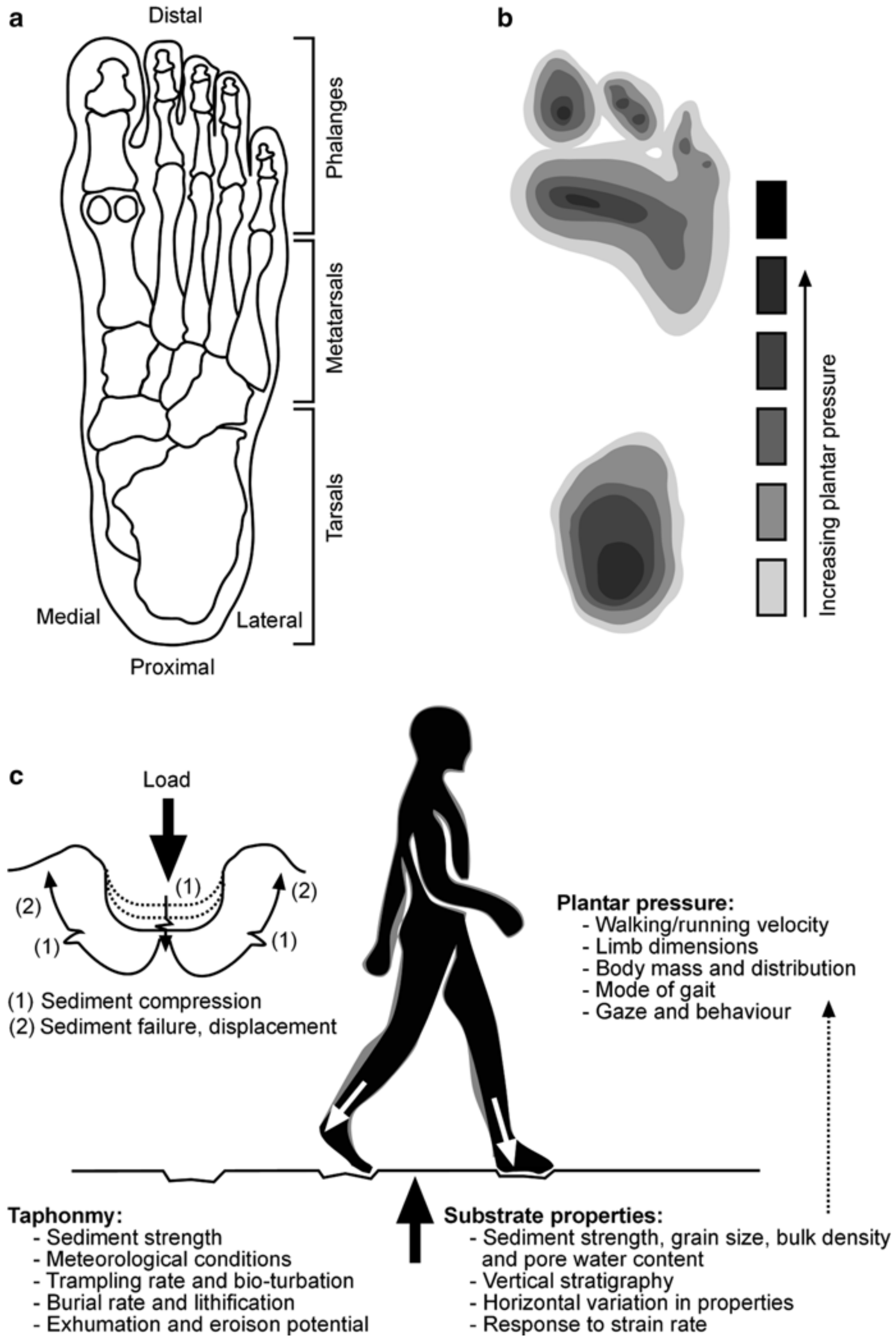

Fig. 1.2 Conceptual model of human footprint formation. (**a**) Sketch of the main bone structures in the foot, plantar view modified from Robbins (1985). (**b**) Stereotypical plantar pressure distribution associated with normal human walking. (**c**) Model of some of the variables involved in the formation of a human track. The *inset* shows the two main ways of strain accommodation in track formation, compression and deformation/displacement

compression, deformation and/or excavation of a track within the substrate assuming that the sedimentary properties which determine the strength of that substrate are exceeded by applied force. Stereotypically the footfall of modern humans and associated pressure path follows a simple pattern, although the variation on this pattern is perhaps more marked than previously thought (Bates et al. 2013a). As the heel first impacts on the ground it creates a rounded impression on a compliant substrate. This is followed by contact with the lateral side of the foot before the pressure transfer medially across the ball of the foot in the latter half of stance, ending over the first and second toe as the foot levers forwards (Elftman and Manter 1935; Morton 1935; Vereecke et al. 2003, 2005). As a consequence typically the deepest part of a footprint should occur beneath the first and second metatarsal heads which along with a deep first toe (hallucal) impression corresponds to the peak pressure at toe-off (Vereecke et al. 2003). The extent to which the lateral toes leave an impression depends on such factors as foot orientation relative to the direction of travel, the precise push-off axes and substrate properties. This simple stereotypical model assumes that plantar pressure or some measure thereof, corresponds in a simple or at least understandable fashion to depth within a given track (Bates et al. 2013b). Effectively one is considering depth an analogue for pressure.

What is not clear is the degree to which this correlation holds true in all circumstances due to the moderation of the pressure recorded by the substrate (Bates et al. 2013b). Leaving this complexity aside for the moment (see Sect. 5.3) one can vary the input of pressure and its time distribution in a number of ways. The most obvious way is to vary the speed at which an individual walks, an increase in speed should increase the force applied to the ground and may also vary the pressure distribution as the bones in the foot lock together more firmly to become a more rigid lever (e.g., Rosenbaum et al. 1994; Burnfield et al. 2004; Segal et al. 2004; Taylor et al. 2004; Warren et al. 2004; Pataky et al. 2008). One can vary the limb properties, chiefly the femur length, and the flexibility of the pelvis and trunk (Levine et al. 2012). To a certain extent this will vary with individual body proportions and pathologies, but is also particularly relevant when examining extinct human species (Vereecke et al. 2005). The centre of mass of an individual may vary and as weight increases which tends to add mass at the front/anterior and therefore impacts on balance and potentially the distribution of pressure through the various stages of stance. The behaviour of the individual may also be relevant; for example their eye gaze, and body/arm orientation may cause variations in pressure as can carrying a bag or an object. There is also an assumption here that unless an individual track-maker has some type of foot pathology the behaviour of their foot is always consistent. This may not always be the case, in some people the foot may show much higher levels of midfoot mobility than is traditionally assumed reflecting midfoot dorsiflexion (mid-tarsal break) and the way the bones lock together to varying degrees in order to form a rigid lever (Bates et al. 2013a). All of these factors make the distribution of plantar pressure for an individual a highly distinct feature, varying to different degrees from the stereotypical pattern (Pataky et al. 2012; see Sect. 7.3). The level of distinction is an intriguing question and critical to understanding the degree to which variation between species can be determined. One needs to not only to understand the degree of inter-species, but also intra-species variation before one can say with any certainty whether these differences are likely to be sufficiently great enough to be revealed in different track topologies.

The other side of the problem is the degree to which the substrate (sediment) actually records gait. Effectively what does the pattern of depth across the plantar surface actually relate to and if this is plantar pressure to what extent is this moderated by sediment properties? There are two elements to this. The first is the degree to which an individual senses a substrate and modifies their gait accordingly. We have all no doubt walked on an icy or muddy surface and as our feet begin to skate loosing traction beneath us we have shortened our stride, slowed our pace, become more tentative in our footfall and subconsciously allowed the flexibility in our foot to compensate for that instability. We shift our weight and therefore pressure to retain balance or flex the toes to acquire more grip and counter any unwanted movement. We are unconsciously modifying our gait and pattern of footfall in accordance with the properties beneath our feet something which is evident when one walks bare foot on the beach and looks at the tracks produced (e.g., Lejeune et al. 1998; Ferris et al. 1999). The very act of extracting a foot from a deep impression may also modify our gait properties. The second way in which substrate impacts on the tracks created is through the properties of the sediment itself. The way in which a substrate accommodates and then holds the void created by the foot will depend on the properties of the sediment and its mobility beneath and around the foot, particularly in the natural shear zone created between the plantar surface of the foot and the base of the track. On a hard and therefore non-compliant surface the foot makes no impression, instead the soft tissue will deform around the skeletal structure of the foot. In completely soft sediment whose strength is far less than the applied pressure, the foot will just sink and continue to do so until it meets with increased resistance. In most situations the sediment consolidates and compresses or a harder substrate is encountered at depth which begins to bear the weight of the individual (Allen 1997). The depth at which this occurs is dependent on the applied force and the vertical stratigraphy of the sediment and the rate of consolidation or strength hardening that occurs. The stability of the track post-formation is also critical; is the material strong enough to withhold the vertical or semi-vertical track walls from collapsing?

The interpretation of human tracks is therefore dependent on several key questions: (1) how unique is the pressure distribution to a given track-maker; (2) what is the range of typical behaviours and patterns for any given human species or set of individuals, and what levels of variance are there around these norms; (3) to what extent does this vary with issues of body mass and behaviour; (4) to what extent can tracks from different substrates be compared; and (5) what variance is there around the sedimentological properties at a given site and how does this add to the variance between tracks in a given trackway? These are the fundamental questions which need to be addressed to interpret human tracks and we will endeavour to address some of them within this volume.

1.4 Track Resources

Throughout this book we use a series of resources to help illustrate a range of aspects. The first of these is based on unpublished track data collected in 2007 by the senior author from 254 individuals working at Bournemouth University (males N = 101; females N = 153; 97 % Caucasian; 2–62 years old with mean of 34 years). Anthropometric data (age, height and weight) were recorded for this sample along with both two-dimensional and three-dimensional tracks. Static two-dimensional tracks, using pressure sensitive paper, were taken of each subject's right foot. At least four tracks were recorded in 3D – two rights and two lefts – walking barefoot at a comfortable/natural speed along an 5 m walk-way the central three metres of which consisted of a sediment tray, 90 mm deep filled with soft damp sand. Individual tracks were photographed and scanned using a VI900 Konica-Minolta optical laser scanner. Contour maps for a series of 12 tracks from this sample are reproduced in the Appendix and are referred to at various points to help illustrate key points.

The second resource used throughout this book are two prominent, in terms of their length, trackways from a site close to Walvis Bay in Namibia and are described by Morse et al. (2013; see Sect. 3.2.3). The longest of these two trails consists of over 70 individual tracks and the local geo-tourist guide who visits the site with a line of clients astride quad-bikes each day describes the trackway as being made by 'Old Harry' on route to the delights of Walvis Bay. The trackway has a consistent step and stride length (0.656 ± 03 m) and stride length (1.386 ± 02 m) and appears to post-date most of the other tracks on the site which consist of both domesticated and wild animals and a large number of short human trackways made by individuals potentially tending and watering flocks. The value of 'Harry's Trackway' is its length and it is introduced here and used throughout the book to illustrate the application of different methods and inferences. While it is not good practice to anthropomorphise, and the gender of the track-maker is unknown, for ease of reference throughout the book we use the term 'Harry's Trackway'. About 8 m to the south is a parallel trackway, consisting of slightly smaller tracks leading the same tour guide to refer to it as 'Harriet's Trackway'. Again we use the colloquial term to identify the trackway but recognise that the gender of the track-maker is not known.

1.5 Summary

In the following chapter we review the range of methodological and analytical tools that are need to study human tracks providing the foundation for what follows. Before looking in detail at how substrate and taphonomy (Chap. 5) may modify the topology of a track and therefore the inferences that can be made from it we provide a review of World tracksites (Chap. 3) in order to give a flavour of the different types of depositional environment in which tracks are preserved and also review some of the challenges associated with their conservation (Chap. 4). In Chap. 6 we explore the inferences that can, and crucially cannot, be made from human tracks and evaluate their value within both archaeology and palaeoanthropology. Based on this Chap. 7 looks at how the study of fossil tracks may help forensic scientists in the study of trace evidence at crime scenes, in the form of footwear and barefoot impression, before we conclude with a brief chapter outlining what we see as the future research agenda for human track studies. This is just one of many ways in which this material could be organised and the book is not necessarily meant to read in linear order, but we do encourage the reader to first look at the methods in Chap. 2 before browsing at their leisure through the later chapters.

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