



**QUEEN'S  
UNIVERSITY  
BELFAST**

## **Biostratigraphic Evidence Relating to the Age-Old Question of Hannibal's Invasion of Italy, I: History and Geological Reconstruction**

Mahaney, W. C., Allen, C. C. R., Pentlavalli, P., Kulakova, A., Young, J. M., Dirszowsky, R. W., West, A., Kelleher, B., Jordan, S., Pulleyblank, C., O'Reilly, S., Murphy, B. T., Lasberg, K., Somelar, P., Garneau, M., Finkelstein, S. A., Sobol, M. K., Kalm, V., Costa, P. J. M., ... Milner, M. W. (2017). Biostratigraphic Evidence Relating to the Age-Old Question of Hannibal's Invasion of Italy, I: History and Geological Reconstruction. *Archaeometry*, 59(1), 164-178. <https://doi.org/10.1111/arcm.12231>

**Published in:**  
Archaeometry

**Document Version:**  
Publisher's PDF, also known as Version of record

**Queen's University Belfast - Research Portal:**  
[Link to publication record in Queen's University Belfast Research Portal](#)

**Publisher rights**  
© 2016 The Authors. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

**General rights**  
Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

**Take down policy**  
The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact [openaccess@qub.ac.uk](mailto:openaccess@qub.ac.uk).

**Open Access**  
This research has been made openly available by Queen's academics and its Open Research team. We would love to hear how access to this research benefits you. – Share your feedback with us: <http://go.qub.ac.uk/oa-feedback>

## BIOSTRATIGRAPHIC EVIDENCE RELATING TO THE AGE-OLD QUESTION OF HANNIBAL'S INVASION OF ITALY, I: HISTORY AND GEOLOGICAL RECONSTRUCTION\*

W. C. MAHANEY,<sup>1,2†</sup> C. C. R. ALLEN,<sup>3</sup> P. PENTLAVALLI,<sup>3</sup> A. KULAKOVA,<sup>3</sup> J. M. YOUNG,<sup>3</sup> R. W. DIRSZOWSKY,<sup>4</sup> A. WEST,<sup>5</sup> B. KELLEHER,<sup>6</sup> S. JORDAN,<sup>6</sup> C. PULLEYBLANK,<sup>6</sup> S. O'REILLY,<sup>6</sup> B. T. MURPHY,<sup>6</sup> K. LASBERG,<sup>7</sup> P. SOMELAR,<sup>7</sup> M. GARNEAU,<sup>8</sup> S. A. FINKELSTEIN,<sup>9</sup> M. K. SOBOL,<sup>9</sup> V. KALM,<sup>7</sup> P. J. M. COSTA,<sup>10</sup> R. G. V. HANCOCK,<sup>11</sup> K. M. HART,<sup>12</sup> P. TRICART,<sup>13</sup> R. W. BARENDREGT,<sup>14</sup> T. E. BUNCH<sup>15</sup> and M. W. MILNER<sup>16</sup>

<sup>1,2</sup>Department of Geography, York University, 4700 Keele Street, Toronto, Ontario M3J 1P3, Canada and Quaternary Surveys, 26 Thornhill Avenue, Thornhill, Ontario L4J 1J4, Canada

<sup>3</sup>School of Biological Sciences, Queens University Belfast, University Road, Belfast BT7 1NN, UK

<sup>4</sup>School of the Environment, Laurentian University, Sudbury, Ontario P3E 2C6, Canada

<sup>5</sup>GeoScience Consulting, Dewey, AZ 86327, USA

<sup>6</sup>School of Chemical Sciences, Dublin City University, Glasnevin, Dublin 9, Ireland

<sup>7</sup>Institute of Ecology and Earth Sciences, University of Tartu, Vanemuise 46-208, 51014 Tartu, Estonia

<sup>8</sup>Centre de Recherche en Géochimie et Géodynamique (GEOTOP), Université du Québec et Montréal (UQAM), CP 8888, Succursale Centre-Ville, Montréal, Québec H3C 3P8 Canada

<sup>9</sup>Department of Earth Sciences, University of Toronto, 22 Russell Street, Toronto, ON M5S 3B1, Canada

<sup>10</sup>Centro de Geologia da Universidade de Lisboa, Faculdade de Ciências da Universidade de Lisboa, Edifício C6, Campo Grande, Lisboa 1749-016, Portugal

<sup>11</sup>Department of Anthropology, McMaster University, Hamilton, Ontario L8S 4K1, Canada

<sup>12</sup>School of Biological and Chemical Sciences, Queen Mary University of London, Mile End Road, London E1 4NS, UK

<sup>13</sup>Institut des Sciences de la Terre, Observatoire des Sciences de l'Univers de Grenoble, Université Joseph Fourier, BP 53, 38041 Grenoble cedex 9, France

<sup>14</sup>Department of Geography, University of Lethbridge, Lethbridge, Alberta T1K 3M4, Canada

<sup>15</sup>Geology Program, School of Earth Science and Environmental Sustainability, Northern Arizona University, 525 S. Beaver Street, PO Box 5694, Flagstaff, AZ 86011, USA

<sup>16</sup>MWM Consulting, 182 Gough Avenue, Toronto, Ontario M4K 3P1, Canada

*Controversy over the alpine route that Hannibal of Carthage followed from the Rhône Basin into Italia has raged amongst classicists and ancient historians for over two millennia. The motivation for identifying the route taken by the Punic Army through the Alps lies in its potential for identifying sites of historical archaeological significance and for the resolution of one of history's most enduring quandaries. Here, we present stratigraphic, geochemical and microbiological evidence recovered from an alluvial floodplain mire located below the Col de la Traversette (~3000 m asl—above sea level) on the French/Italian border that potentially identifies the invasion route as the one originally proposed by Sir Gavin de Beer (de Beer 1974). The dated layer is termed the MAD bed (mass animal deposition) based on disrupted bedding, greatly increased organic carbon and key/specialized biological components/compounds, the latter reported in Part II of this paper. We propose that the highly abnormal churned up (bioturbated) bed was contaminated by the passage of Hannibal's animals, possibly thousands, feeding and watering at the site, during the early stage of Hannibal's invasion of Italia (218 BC).*

\*Received 20 June 2015; accepted 11 November 2015

†Corresponding author: email arkose41@gmail.com

The copyright line for this article was changed on 27 July 2016 after original online publication.

© 2016 The Authors.

Archaeometry published by John Wiley & Sons Ltd on behalf of University of Oxford

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

**KEYWORDS:** HANNIBALIC WAR, SECOND PUNIC WAR, ENVIRONMENTAL PARAMETERS, INVASION ROUTE QUESTION, HANNIBAL ROUTE ENIGMA UNMASKED

## INTRODUCTION

The main approach routes (Livy, 1965; Proctor 1971; de Beer 1974; Polybius 1979) and associated mountain passes (cols) identified as likely transit points of Hannibal's army into Cisalpine Gaul (northern Italy) have been debated and discussed by historians for over two millennia (Freshfield 1886, 1899; Dodge 1891; Wilkinson 1911; de Beer 1956, 1967, 1969, 1974; Connolly 1981; Seibert 1993; Lazenby 1998; Bagnall 1999; Lancel 1999; Mahaney 2004; Mahaney *et al.* 2007b, 2008a, 2008b, 2008c, 2010a, 2010b, 2010c, 2014). These invasion passages are referred to here as the southern, northern and intermediate routes, as shown in Figure 1 (Hart 1967; Proctor 1971; de Beer 1974). The southernmost follows the lower Rhône River valley northwards to the Drôme River, thence across the Col de Grímone (1318 m; Alpes du Dauphiné) to the Durance Basin, through the Queyras (Guil River) to the Col de la Traversette, finally exiting through the two-tier rockfall similar to that described by Polybius (1979) into the upper Po River catchment. The northern route parallels the Rhône River to the Isère River, past present-day Grenoble along the Arc River to either the Col du Mont Cenis (2083 m) or the Col du Clapier (2497 m), finally exiting into the Dora Riparia west of Torino (Turin in Fig. 1). The intermediate route follows the same initial course as the northern route, then west of the Pelvoux

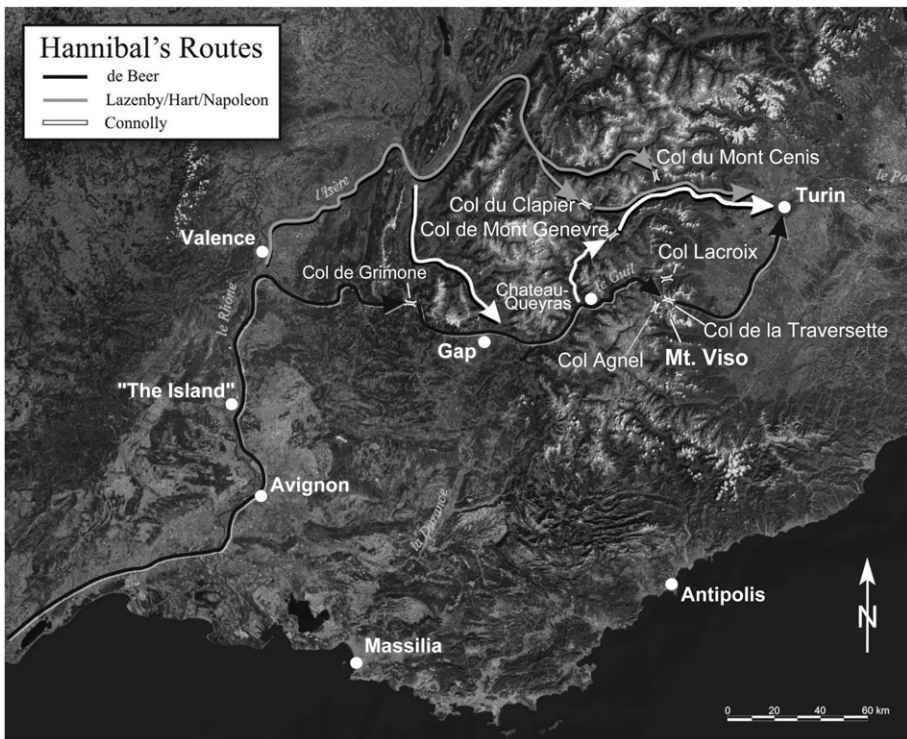


Figure 1 A satellite image showing the terrain of the Western Alps and the three prominent invasion routes considered by most authorities to demarcate Hannibal's route into Italia in 218 BC (courtesy of NASA and USGS).

Massif to join the Durance River continuing towards the Col de Mont Genèvre (1830 m), exiting into the Dora Riparia.

After two millennia, the question remains unsettled of the specific path over the Alps taken by Hannibal or by Hasdrubal, his brother, who followed him 11 years later (Proctor 1971; Lazenby 1998; de Beer 1974). However, time–motion analysis of these three potential routes, and investigations of each pass into *Italia* carried out by Mahaney (2008) revealed the southern route to be the most direct and highest track into northern Italy from the Rhône Basin, and all authorities agree that Hannibal had to march with speed to cross the Alps before winter set in. Furthermore, Polybius (1979), a primary ancient authority who interviewed survivors of the invasion and retraced the invasion route some 60 years after the fact, is definite that Hannibal descended upon the Po River plains rather than the Dora Riparia approximately 50 km to the north.

Uncertainty regarding Hannibal's route stems from contested interpretations of ancient place names, preferential use of either Livy (1965) or Polybius (1979) as a primary ancient source (the two are not compatible) and competing views by other historians of travel times between points.

Traditional arguments have not relied on physical or environmental parameters (Mahaney 2008), because no physical artefacts (nails, coins, buckles etc.) have ever been found on any of the potential alpine routes. However, organic compounds associated with people and animals can easily persist for several millennia and are easy to detect, leading us to hypothesize that Hannibal's army and his horses/mules/elephants may have left organic evidence of their passage. To investigate this possibility, we located a site at ~2580 m asl along the southern route in the Alps that could have been used as a campsite for a large group of people and animals (~30 000 infantry, ~7000 cavalry, unknown number of handlers and 37 elephants; Lancel 1999) (Fig. 2). Then, we used multidisciplinary techniques to search for pedological, micropalaeontological, biochemical and lipid biomarker evidence that might help determine if the site was along Hannibal's invasion route.

#### ENVIRONMENTAL FACTORS

There are distinctive topographical landmarks for the Hannibalic route that are identified in the ancient literature (Proctor 1971; de Beer 1974; Polybius 1979; Mahaney 2008; Mahaney *et al.* 2014). These include a gorge on the approach to the summit, a 'certain bare rock', a bivouac near the col, a view into *Italia*, fired rock and a regrouping area, and all of these elements are common to most potential invasion routes. However, the only route that meets two key historical descriptions—the rockfall and frozen ground—is the southern route across the Col de la Traversette into the Po River plains of northern Italy.

Of all environmental factors used to identify the invasion route (Mahaney 2008), there are two paramount clues. The first is the superposed two-tier rockfall described by Polybius (1979). It is interesting that of all the repeat histories published over the years, and quotes from both Livy and Polybius, few, if any, have focused on Polybius' mention of a two-tier deposit, one mass produced by two mass wasting events. Following a survey of all likely passes used by the Punic Army (Mahaney 2008), the only such rockfall debris below all the cols that could have blocked the infiltrating army is located on the lee flank of the Alps in the upper Po Valley, below the Col de la Traversette (Mahaney *et al.* 2010c, 2014) at 2600 m asl.

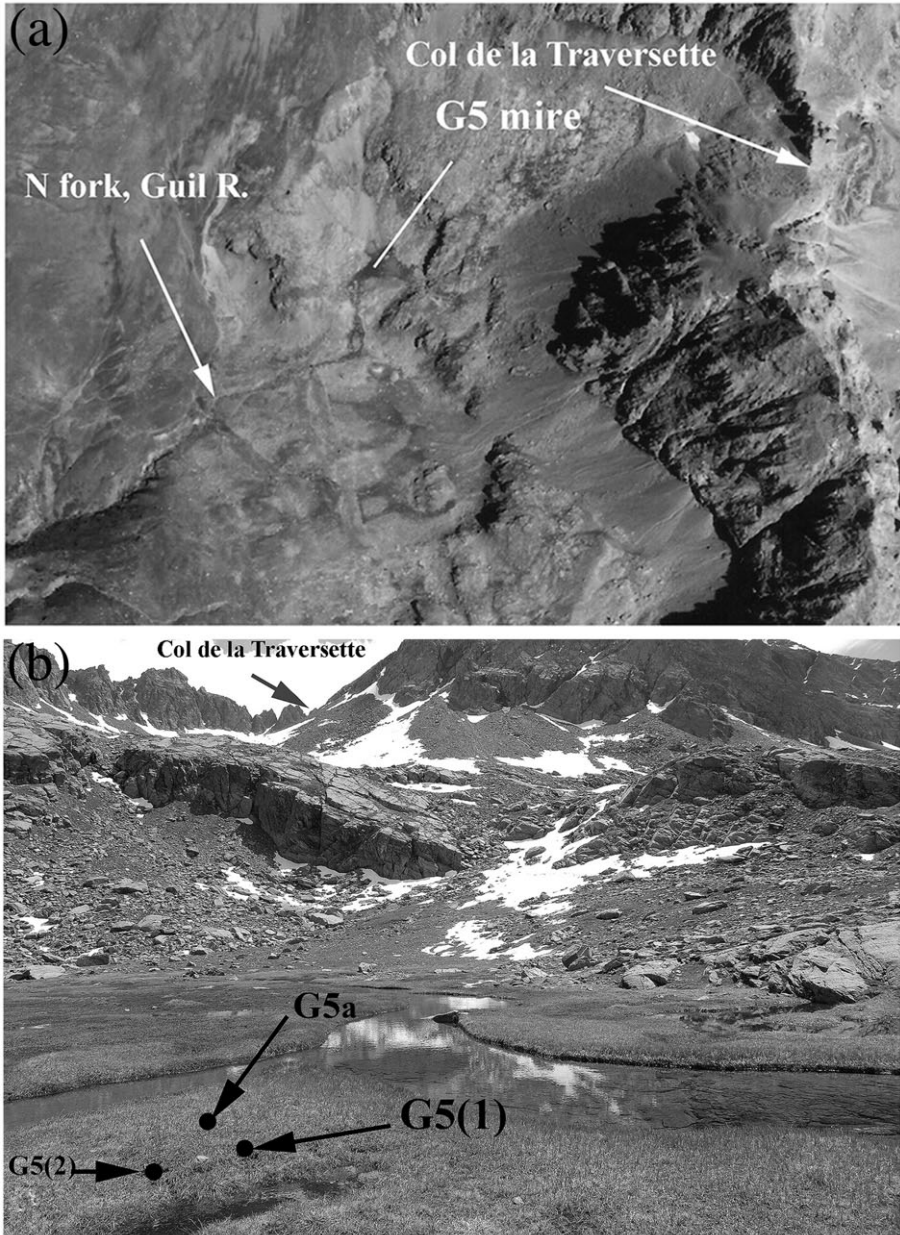


Figure 2 (a) Air-photographic coverage of the core/section sites relative to the Col de la Traversette, Hannibal's proposed transit pass into Italia. (b) Core/section sites at the G5-G5a sites relative to the north fork of the Guil River.

Perhaps relying on a first-hand account by Silenus (Hannibal's historiographer; Lancel 1999), Livy maintained (Livy 1965, XXI, 37) that the rockfall provided such an impediment to passage of the army that Hannibal ordered its firing to allow the passage of the horses and elephants. According to this account, wood was brought to the site at 2600 m asl, then set alight, producing

sufficient heat to physically disrupt and crack boulders that could not be moved by hand. Bagnall (1999) questioned Livy's interpretation, arguing that green wood would not be expected to burn. Wood might have been available up to perhaps 2400 m asl (Mahaney *et al.* 2010b), provided that one might expect starving soldiers to be capable of harvesting/transporting it to the rockfall, also a doubtful outcome. Not even Kuhle and Kuhle (2012), who mention the firing event, were able to substantiate how it might apply to the northern route across the Col du Clapier, their preferred route of passage. Previous work by Mahaney (2013) showed conclusively that while the rockfall described by Polybius exists below the Col de la Traversette, there is no evidence that it was fired, as no carbonized/split boulders are resident in the rockfall mass (Sodhi *et al.* 2006). Moreover, Polybius is mute on the firing event, and since he was the prime authority who followed the invasion route, the obvious conclusion is that, despite its perpetuation, the firing never happened.

The second vital clue is the presence of frozen ground. Sporadic permafrost, where present today, is deeply buried in the Western Alps (Mahaney *et al.* 2007a), and that was probably true in Hannibal's time, because today's climate is similar (Neumann 1992). Thus, it is likely that the major terrain obstacle of frozen ground referred to by Polybius (1979) was not permafrost but, rather, discontinuous frozen soil or firnpack (dense snow) covered with fresh snow. The Col de la Traversette, compared to the other mountain passes, is the only pass that reaches to within the snowline (~2800 m asl), with discontinuous permanent snow (firnpack). At lower elevations, the Col Agnel and the Col la Croix, adjacent to Traversette (Fig. 1), provide somewhat shorter routes into Italy, but lack firnpack, which is a prerequisite to identifying the correct col. Moreover, none of the other major cols—Clapier, Genève and Cenis—have permanent snow/firnpack or blocking rockfall, which is why de Beer (1974) and other researchers (Mahaney 2008) favoured the Traversette as the route Hannibal used to cross the Alps. Even with elevations imprecisely known at the time, Polybius's (1979) description of the invasion route strongly suggests the Traversette as the crossing point into the peninsula, an inference supported by Varro's mention in *De re rustica* (quoted by Proctor 1971) of the passes in geographical order from north to south—'Hannibal's Pass' lying south of the Col de Genève (Fig. 1). Moreover, reference to Varro's mention of the five cols, including Hannibal's Col as the highest, is quoted in Servius' commentaries, translated in Savage (1934).

In addition to the two-tier rockfall and the presence of frozen ground, a third requirement for a successful passage into Italy is the presence of forage plants (grasses and sedges) and sufficient watering holes for animals and humans alike. If the Col de la Traversette is the route taken by Hannibal, as all topographical data indicate (Mahaney 2008), the mire sites investigated here (G5 and G5a—described below) could have provided an area of forage and fresh water for use by Hannibal's troops and animals. The mire evidence presented here strongly supports previous estimates that the southern route through the Traversette was the route taken by Hannibal.

#### SITES

Recently, Mahaney (2008) used time–motion analysis, elevation modelling and field observations on sites along the southern route originally favoured by de Beer (1974) to identify potential hearths and watering hole/feeding grounds that might have been used by the Punic Army during transit. The army would have had access to stream water in many places along the Guil catchment (west flank), but there are only a few grassy and level areas above 2000 m asl upon which to graze horses and provide feed. After searching those areas for soils composed mainly of

organic materials (Histosols; Soil Survey Staff 1999), we located a candidate site ~425 m below the Col de la Traversette. The ~60 × ~40 m wide location (latitude/longitude: 44°42' 587N; 07° 032 74E; 2580 m asl), designated G5 and G5a, is the only organics-rich peat bed (mire) above 2000 m asl in the Guil Valley along the southern route to the Col de la Traversette. It lies 30 m higher than nested Late Glacial (~13–15 ka) and Younger Dryas (~11–13 ka) moraines in the lower Guil Valley (Mahaney and Keiser 2012; Mahaney *et al.* 2013) and below the level of nearby talus, all of which are Little Ice Age (LIA) or post-LIA in age. Therefore, sediments of Hannibalic age should be present.

The site is located on a gently sloping bedrock bar composed of metabasalt (Tricart *et al.* 2003), lying adjacent to the headwaters of the Guil River and, therefore, is subject to periodic overbank flooding. The stratum overlying the flood-derived sediments consists of ~1 m of organic-rich, alluvial mire (Fig. 2). In summary, the mire comprises one of the few near-level, forage-covered watering holes in the upper Guil catchment, located astride the southern route approaching the Col de la Traversette. Thus, it would have provided a prime watering hole, if Hannibal's cavalry and pack animals passed this way *en route* to the mountain pass.

#### MATERIALS AND METHODS: THE GEO-RECORD

Two cores [G5(1) and G5(2) (Fig. 2 (b)); ~68 cm depth] were recovered from the mire in 2011. The cores provided radiocarbon ages, along with preliminary stratigraphic and geochemical data that, in turn, led to the excavation of an adjacent trench (G5a) to a depth of ~75 cm in 2013 (Fig. 3 (a)). A photograph of the excavated section from 0 to 38 cm (Fig. 3 (a)) shows that the horizontal bedding of the trench matches that in the macrophotograph of the combined core (Fig. 3 (b)).

Cores were recovered using 5-cm diameter PVC tubes fitted with a core catcher and were stored cool until opened in the laboratory. Colours were determined using the colour chips of Oyama and Takehara (1970); G5 under dry conditions in the laboratory and G5a in the field. In the laboratory, cores were split and allowed to dry slightly to improve handling prior to sedimentological description, surface penetration, photography and subsampling. Since the two cores were stratigraphically correlated, they were combined into one single core to increase sediment volume for analysis subsection by subsection (Fig. 3 (b)).

Sediment samples acquired from the trench and the two cores (Fig. 3 (b)), provided measurements of organic carbon, bulk density and moisture. Subsamples (~1 cm<sup>3</sup>) were removed with a stainless steel knife at 5-cm intervals. One set of samples was oven dried at 60 °C for 24 h, and the moisture content and the wet and dry bulk density calculated based on weight change and subsample dimensions. The total organic matter content was estimated from the basic sequential LOI (550 °C/1 h) using a muffle furnace. Elemental analysis was also performed in triplicate on the 2013 G5a samples, using a Fisons NCS 1500 NA elemental analyser.

The mineralogy of the G5a section was investigated by SEM/EDS (for more information on SEM imagery interpretation, see Mahaney 2002) and XRD at various depths to determine composition and variations. The quantitative mineralogical composition was interpreted and modelled by the Rietveld algorithm-based program Siroquant-3 (Taylor 1991).

Pollen was analysed from 10 samples in the GUIL5a sequence (depths 5, 15, 20, 25, 30, 35, 40, 45, 50 and 55 cm). Samples were prepared using standard methods, including digestions in 10 % HCl, 10 % KOH, concentrated HF and acetolysis, and mechanical separation using 10-µm and 150-µm sieves. Dehydrated residues were stored in silicone oil and mounted for light microscopy. Pollen grains were enumerated under brightfield optics at ×400 magnification, and

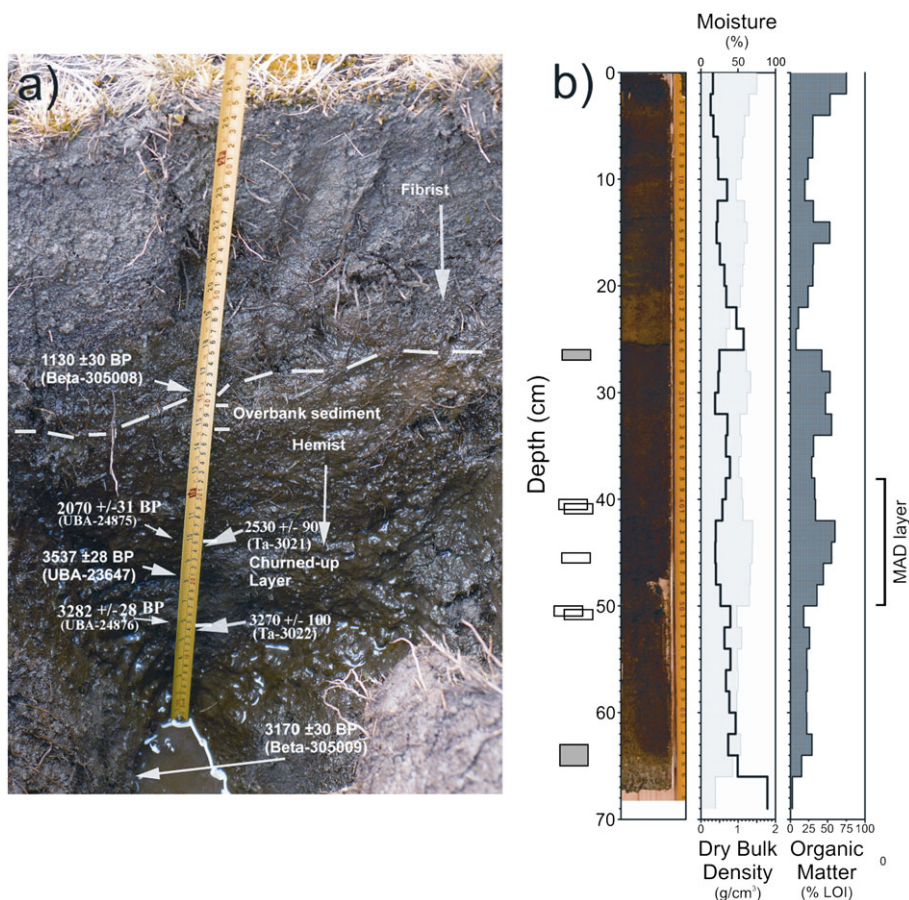


Figure 3 (a) The excavated sedimentary section G5a ( $44^{\circ} 42' 588N$ ;  $7^{\circ} 03' 281E$ , 2573 m asl). Hannibal's invasion coincides with the age of the top of the churned-up layer. All dates are OxCal v.4.2.4 calibrated dates. Open symbols are dates from the section; closed symbols are dates from the core. The dashed line is the contact between the Fibrist (undecomposed organics) and Hemist (moderate organic decomposition) suborders of the Histosol order (Soil Survey Staff 1999). The base of the overbank sediment probably corresponds to an unconformity hiatus produced by erosion accompanying deposition of the overbank sediment. (b) The G5 core, showing macrophotography, moisture (light grey), bulk density (solid line) and organic carbon. The MAD bed centres on  $45 \pm 5$  cm in this image, but varies up to  $\sim \pm 10$  cm. The basal sediment (unsampled) is  $\sim 5$  cm alluvium over bedrock. Depths of units in the section (G5a) and core (G5) are offset by  $\sim 5$  cm between the two sites.

identified using standard references (Moore *et al.* 1991). A main pollen sum consisting of trees, shrubs and herbaceous taxa was used to calculate percentages of all taxa. Aquatic pollen types were excluded from the sum; percentages of aquatic taxa were determined on the basis of the main sum.

All  $^{14}C$  dates are from peat samples in two cores and one trench. These were prepared by accepted standards, stored cold/frozen until dating by conventional or AMS means at the Queen's University Belfast CHRONO dating centre, at Beta Analytic and at the Radiocarbon Laboratory at the University of Tartu, Tartu, Estonia.

Radiocarbon dates were adjusted by  $^{13}C$  and calibrated using IntCal-13 in OxCal v.4.2.4 (Bronk Ramsey 2009; Reimer *et al.* 2013), and then further modelled using Bayesian statistical



analyses. The first four columns in Table 1 show laboratory numbers, uncalibrated  $^{14}\text{C}$  dates with uncertainties and depths below surface. The two dates highlighted with lighter shading bracket the age of Hannibal's invasion in darker shading. The four columns show the calibrated ages of the radiocarbon dates at one and two standard deviations. The next four columns under 'Modelled' show the Bayesian-derived ages (Bronk Ramsey 2009) at one and two standard deviations. The last column shows the calculated agreement index values for the model ( $A_{\text{model}}$ ) and overall ( $A_{\text{overall}}$ ), each of which is at >95% probability. For simplicity, the rows are grouped into pre-invasion beds, post-invasion beds and MAD bed (mass animal deposition).

## RESULTS AND DISCUSSION

### Stratigraphy

Four stratigraphic subsections were identified. The uppermost and youngest (post-invasion subsection II) extends from 0 to 26 cm depth. We term this the post-invasion section. In the excavated trench, the exposed soil (Fig. 3 (a)) contains an organic-rich surface horizon that exhibits a variable black colour (10YR 2/1 to 10YR 2/2), with intact fibre and roots present near the surface that exceed the 20 cm depth of peat requirement for Histosols. This unit displays increasing overbank sedimentation and decreasing organic input with depth, culminating in a 5-cm-thick, unweathered, silty sand bed (Fig. 3 (a)), showing increased bulk density, but with little organic content or moisture (Fig. 3 (b)). This sand bed is composed mostly of overbank sedimentation that began at AD 1350, or ~600 calendar years before present (cal BP), prior to the Little Ice Age (LIA) climatic deterioration starting *c.* AD 1500. The increase of organic matter above the sand bed upwards to the ~15 cm depth records plant growth during the Medieval Warm Period (MWP), prior to the onset of the LIA, and is paralleled by elevated faecal biomarker signals described in Mahaney *et al.* (2016). Above this, the low increases of organic matter document a slow but punctuated rise in organic carbon throughout the top 10 cm of the profile.

Moving downwards, the next post-invasion subsection (I) extends from 26 to 38 cm depth, and is comprised of more highly decomposed soil (Hemist, Soil Survey Staff 1999; Fig. 3 (a)), most

Table 1 Radiocarbon dates and the age-sequence model (OxCal v.4.2.4): laboratory numbers, uncalibrated  $^{14}\text{C}$  dates with uncertainties, depths below surface, calibrated ages and Bayesian modelled ages

Laboratory number	$^{14}\text{C}$	$\sigma$	Depth (cm)	Unmodelled				Modelled				$A_{\text{model}} = 97.6$
				$\mu$	$\sigma$	$2\sigma$ : from	to	$\mu$	$\sigma$	$2\sigma$ : from	to	
Beta-305008	1130	30	26	1035	48	1173	962	1009	271	1456	392	$A_{\text{overall}} = 97.6$
<b>Post-invasion beds</b>												
Transition								1704	375	2356	997	
UBA-24875	2070	31	40	2042	46	2125	1949	2079	220	2464	1597	99.1
<b>Hannibal: 218 BC</b>												
Ta-3021	2530	90	40	2587	117	2769	2357	2464	307	3002	1804	100.2
UBA-23647	3537	28	45	3811	52	3895	3720	2866	390	3509	2109	98.3
Ta-3022	3270	100	50	3509	118	3820	3249	2840	435	3544	1982	99.3
UBA-24876	3282	28	50	3511	36	3573	3450	2919	347	3462	2265	99.4
<b>MAD bed; Hannibalic invasion</b>												
Transition								3242	281	3684	2610	
Beta-305009	3170	30	65	3398	33	3454	3345	3417	206	3765	2939	99.3
<b>Pre-invasion beds</b>												

probably caused by stream migration away from the site of deposition that caused increased organic/peat accumulation with moderate but variable decomposition. All organic material in this interval exists as finely disseminated peat lacking any fibrous character, except for a few narrow roots. At 26–27 cm, a calibrated radiocarbon age of  $1035 \pm 48$  cal BP (Beta-305008) dates the upper part of this section to within the beginning of the MWP at  $\sim 1200$  cal BP (*c.* AD 950). This interval is organic-rich with parallel beds and is presumably a product of increased humidity and temperature.

The next subsection (III, or MAD) extends from 38 to 50 cm, and near the top at 42 cm, the bulk density drops to its lowest level in the core, except for surface samples (Fig. 3 (b)). At the same time, the organic content rises to its highest level below surface values, and the sediment colour becomes darker black, with a solid colour expression of 10YR 1/1. This interval consists of an open structure of loosely matted organic fragments mixed with finer decomposed material, suggesting that it has been mixed or churned (bioturbated). This churning is rarely, if ever, seen in bog cores elsewhere in alpine or other areas (for examples, see Mahaney 1990, figs 7.4 and 7.5).

For the lower part of subsection III, there are three calibrated radiocarbon dates— $3507 \pm 118$  cal BP (Ta-3022),  $3511 \pm 36$  cal BP at 50 cm (UBA-24876) and  $3811 \pm 52$  cal BP at 45 cm (UBA-23647)—all of which predate Hannibal's invasion. However, at 40 cm in the upper part of this subsection, there are two calibrated radiocarbon dates, of  $2042 \pm 46$  cal BP (UBA-24875) and  $2586 \pm 117$  cal BP (Ta-3021), that bracket the invasion year of 2168 cal BP (218 BC). Using Bayesian analysis in OxCal v.4.2.4 (IntCal-13 calibration curve), we calculated an age model for the entire stratigraphic sequence (Fig. 4), yielding a modelled age that firmly places the age of the upper portion of subsection III at the time of Hannibal's invasion of Italy in 218 BC (2168 cal BP).

Based on the evidence, we interpret the upper part of this churned-up (bioturbated) layer as most closely representing Hannibal's invasion, which produced the MAD bed. The older and deeper part of this subsection is interpreted to result from human/animal traffic, possibly from

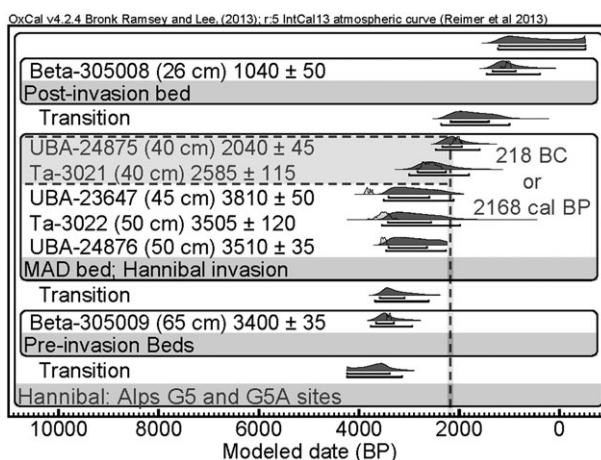


Figure 4 Bayesian analyses of  $^{14}\text{C}$  ages in the G5b core and G5a section, Guil River catchment, Mt Viso area, western Alps. OxCal v.4.2.4 calculated >14 million combinations of possible ages and uncertainties to determine the most probable age model, which places the Hannibalic invasion event as predicted, at the top of the MAD (mass animal deposition) bed, with a high probability of >95%.

activity of Hannibal's army that disturbed and churned pre-existing, stratified organic beds into one massive, non-laminated bed of finely disseminated peat. The increase of organic carbon and moisture, originating from trampled vegetation and dung from animals, provided an organic base supporting the ingress of *Clostridia*, a prominent endospore-producing bacterial component of the mammalian gut, as discussed among biological contingents in Part II.

For the pre-invasion subsection below 50 cm (subsection IV), the stratified base of the core at ~68 cm depth yields a calibrated age of  $3400 \pm 35$  cal BP (Beta-305009) that is slightly younger than the three dates above it, thus supporting the interpretation of sediment reworking due to a mass invasion of animals and humans in the overlying MAD bed. The bottom of the core to 80 cm crumbled upon recovery and provided little usable data. The total core depth of 68 cm, comprising variable organic matter content, yields an estimated sedimentation rate of  $5 \text{ mm yr}^{-1}$ .

### *Mineralogy and geochemical analysis*

The G5–G5a section data recorded here provide palaeoecological and geochemical data adding to the corpus of information previously reported for the Traversette area (Mahaney *et al.* 2010b).

Primary minerals follow from the local metabasalt bedrock, with detrital species of Ca-plagioclase, albite, amphibole, antigorite, opal phytolith and micron/submicron organic materials mostly adhering to primary mineral grains. Opal phytoliths are derived from plants that incorporate silica from the soil, depositing it within the intracellular and extracellular plant structure. As plants decay, silica remains as a weathering-resistant, almost elliptical microscopic mineral (Alexandre *et al.* 1997).

Because leaching might affect the distribution of organic compounds within the cores, ratios of soluble to insoluble macroelements such as Ca/Ti, Na/Ti, Ca/Al, Na/Al, P/Ti and P/Al were studied to test for translocation. These chemical element ratios show no evidence of leaching through the core or trenched section, although minor fluctuations occurred with organic dilution of the mineral component or high mineral content as in the sandy bed at 26–30 cm depth.

The 20–40 % organic matter staggered through the G5 section (Fig. 3 (b)), coupled with the 60–80 % mineral content by weight, affords considerable physical stability to the peat beds. This is further indicated by the out-of-phase organic matter to bulk density measurements in Figure 3 (b) that support field observations depicting a stable, semi-dry peatland, wet at the base and becoming progressively drier upwards in the section (see the macrofossil evidence below).

### *Palaeoecological analysis*

Macrofossil analyses of the entire G5 core showed a dominance of herbaceous assemblages, corresponding well with a reconstructed climate record (Neumann 1992) for the Western Alps with near-unvarying temperature/precipitation straddling the time of the Hannibalic invasion. At the base (65–50 cm), the abundance of *Typha* seeds confirms an open freshwater marsh condition. From 15 cm to the surface, conditions became drier, as suggested by the introduction of *Sphagnum* spp. followed by ligneous species at the surface of the site.

While palaeoecology studies for Early to Late Holocene time periods are rare in the Southern Alps, the Swiss (Valsecchi and Tinner 2010) document sections, some at high elevations, similar to sections reported here. Coincidentally, these authors report  $^{14}\text{C}$  dates in peat, at 35 cm depth, to  $890 \pm 60$  yr BP ( $700\text{--}900$  cal yr), correlating close to MWP dates reported herein.

Pollen (Fig. 5) was analysed from 10 samples in the GUIL5a sequence. Pollen grains were abundant and well preserved throughout. The mean pollen sum was 195 grains (min.–max. = 119–380); the mean total number of grains counted was 333 (min.–max. = 218–457). The pollen assemblages confirm the persistence of the alpine mire through the period of record. The assemblages are dominated by pollen of Cyperaceae, *Alnus*, upland herbaceous taxa (including Poaceae) and needle-leaved trees. The percentage of tree pollen is low through the sequence. Needle-leaved taxa dominate the tree pollen assemblages, and reflect transport from local and regional montane forests at treeline or below. Broad-leaved trees are recorded at low abundance throughout (generally <3%, with a maximum of 8% at depth of 15 cm), reflecting the high-elevation setting of the site and the low local abundance of broad-leaved trees. Shrub pollen is present at moderate abundance, dominated by *Alnus* types, and probably reflects local mire dynamics. The pollen assemblages broadly support the four zones presented above. The upper section (0–25 cm) is characterized by a minor up-core decrease in needle-leaved tree pollen, which may reflect a shift in the position of the treeline or in forest composition with climatic changes associated with the MWP-to-LIA transition. A modest increase in herbaceous taxa, bryophytes, ferns, fern allies and shrubs also occurs from 25 cm and above, which supports the interpretation from macrofossils and other proxies of a drier mire surface. These changes could also, in part, reflect land-use change and forest clearance, supported by increases in pollen of Chenopodiaceae/Amaranthaceae in the upper samples. The middle portion of the pollen sequence is characterized by moderate abundances of Cyperaceae pollen, corresponding to the lower post-invasion zone. The MAD section (38–50 cm) corresponds to a large peak in Cyperaceae pollen. Below the MAD section, Cyperaceae pollen drops significantly, and the assemblages are dominated again by needle-leaved trees and upland herbs, including Poaceae.

The strongest signals in the pollen record are in the local wetland pollen types, particularly Cyperaceae. The Cyperaceae (sedges) are a large family of plants found in a variety of aquatic habitats, and are common dominants in alpine meadows (Cronk and Fennessy 2001). Cyperaceae pollen may be locally very abundant in sediment records, and thus Cyperaceae pollen

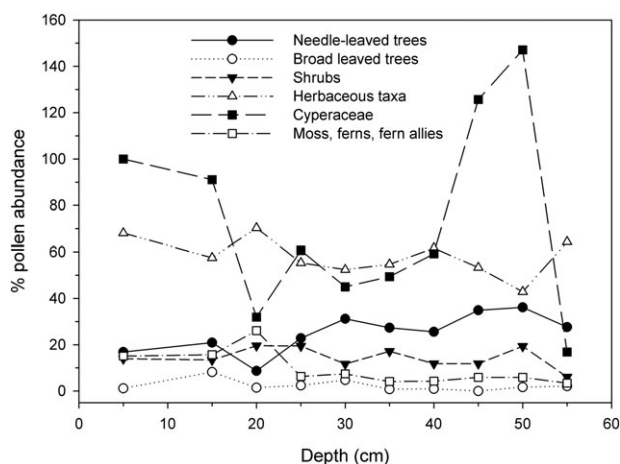


Figure 5 A summary of the pollen data for GUIL5b. Pollen types are expressed as percentages of the main pollen sum, which excludes aquatic taxa (Cyperaceae). Needle-leaved trees include *Abies*, *Larix*, *Picea* and *Pinus*; herbaceous taxa include Poaceae, among other types. The raw data can be accessed by contacting Sarah Finkelstein ([finkelstein@es.utoronto.ca](mailto:finkelstein@es.utoronto.ca)) and/or Magda Sobol ([magdalena.sobol@mail.utoronto.ca](mailto:magdalena.sobol@mail.utoronto.ca)).

abundances are generally interpreted as indicative of local mire processes (Miola *et al.* 2006). Cyperaceae pollen is not reliably identified to genus or species (Moore *et al.* 1991); thus, the pollen percentages in the GUIL5a record probably include several genera and species, each of which may vary in terms of ecological preferences. Because of the strong affinity for aquatic habitats, fluctuations in Cyperaceae pollen tend to be interpreted as signals for fluctuations in water level. However, some Cyperaceae are emergent plants in standing water while others are associated with mesic but aerated forest soils (Cronk and Fennessy 2001), making inference of absolute changes in the position of the water table based solely on Cyperaceae pollen difficult. The increase in Cyperaceae pollen in the upper section of the GUIL5a record, coincident with other indicators of drying, probably reflects a shift in species composition of Cyperaceae in response to a drying mire surface.

The spike in Cyperaceae in the MAD bed (38–50 cm) is less likely to be a response to a change in the position of the water table, because of the rapidity with which this section was deposited, based on the radiocarbon age model. Thus, the spike in the Cyperaceae pollen may be interpreted as further support for human passage through this section. Cyperaceae frequently dominate in alpine meadows. While animals tend to prefer grasses to sedges for grazing, sedges will be grazed upon when grasses are not available (Elliott and Henry 2011). Given the evidence for faecal matter in the MAD section (see Part II), it is possible that the Cyperaceae peak in the MAD layer reflects the deposition of pollen grains through animal guts following the passage of large numbers of grazing animals. Pollen grains survive gut passage; coprolites have been used as sources of palynological information in a variety of contexts (Carrion *et al.* 2001; Kropf *et al.* 2007).

### *Transhumance*

Transhumance has been practiced for millennia in the Western Alps (Schwörer *et al.* 2014) and, as Walsh *et al.* (2007) have shown, human activity (including transhumance) accelerated during the last millennium in the Parc National des Ecrins, Hautes-Alpes, sites located near Mt Viso. Archaeologists are divided over the extent to which environment determines human activity, with some pro (Leveau 2007) and others con (Walsh 2005). Transhumance may be read into the slight increase of faecal biosignatures recorded during the MWP part of the G5–G5a sections, at depths < 30 cm. However, these sediments lack evidence of the kind of major bioturbation observed in the MAD bed. There is nothing to indicate a high level of animal (including human) disturbance in the two sections other than what exists in the MAD bed (~45 cm). Furthermore, the abundance of bacteria—endospores for the most part—sourced specifically from mammals and located primarily within the churned-up beds (see Part II), could only result from the passage of hundreds, if not thousands, of animals, indicating movement of something more than animals involved in tribal trade.

## CONCLUSIONS

Previous analysis of environmental factors has strongly favoured the southern route for Hannibal's passage through the Alps. In addition to features indicated by ancient authors, including the presence of frozen ground and the two-tiered rockfall, there must have been sufficient grounds for grazing large numbers of army animals, including horses and elephants.

The highly anomalous MAD sediments recovered in cores from site G5 and the G5a section in the upper Guil Valley reveal intensive convolution of organic sediment, indicating major disturbance to the beds. Radiocarbon-dating indicates that this disturbance occurred

within the Hannibal window. This extensive churning observed in the MAD layer suggests trampling/disaggregation of organic layers by animals, and possibly humans as well, that cannot be accounted for by small-scale transhumance. The MAD layer contains a spike in Cyperaceae pollen, which may be indicative of the passage of large numbers of grazing animals. The beds also feature strong faecal biosignatures and the presence of bacteria from mammals, discussed in Part II.

This may be the first tangible, if unusual, evidence of human/animal activity at the time of Hannibal's invasion of *Italia*. Although we cannot determine conclusively that the evidence pertains to Hannibal, the results are consistent with the passage of large numbers of animals and people, and because of the high elevation, are inconsistent with normal transhumance in the area. If confirmed, the findings presented here have far-reaching implications for solving the Hannibalic route question and, more importantly, for the identification of a site that might be expected to yield significant historical archaeological data and artefacts related to the Punic invasion. If the site was affected by human–animal traffic, as the evidence indicates, there is every possibility that artefacts such as coins, belt buckles, daggers, equestrian fasteners and so on might have been buried in the mire. If such archaeological evidence can be found and definitively linked to Hannibal, it would answer the question of which route Hannibal and his army took into *Italia*.

#### ACKNOWLEDGEMENTS

This work benefitted from conversations/correspondence with John Lazenby (University of Newcastle) and Craig Hanyan (Brock University, St Catharines, Ontario, Canada). The satellite imagery in Figure 1 was provided by Trent Hare, USGS, Flagstaff, Arizona (credit JPL, NASA/USGS). We gratefully acknowledge assistance from Sarah and Paul Ginty-Ciselar, custodians of the Refuge du Viso, License granting authority of the Préfet des Hautes Alpes, to conduct excavations on the French side of the Traversette (Réserve Naturelle Ristolas-Mont Viso), and staff of the Pian del Re and Giacoletti refuges in the upper Po River catchment. We also acknowledge funding support from the QUESTOR centre (PP), the Invest Northern Ireland Grant for R&D programme (CCRA), Invest Northern Ireland (AK), the Geological Survey of Ireland (INFOMAR) and the Irish Research Council (RS/2012/499, BK), H2020 REMEDIATE Marie Curie ETN, Grant agreement no. 643087 (BK), Quaternary Surveys, Toronto and research/travel grants (YU-493885) from York University, Toronto (WCM).

#### REFERENCES

- Alexandre, A., Meunier, J., Colin, F., Koud, J., 1997, Plant impact on the biogeochemical cycle of silicon and related weathering processes, *Geochimica et Cosmochimica Acta*, **61**, 677–82.
- Bagnall, N., 1999, *The Punic wars*, Pimlico, London.
- Bronk Ramsey, C., 2009, Bayesian analysis of radiocarbon dates, *Radiocarbon*, **51**, 337–60.
- Bronk Ramsey, C., and Lee, S., 2013, Recent and planned developments of the program OxCal., *Radiocarbon*, **55**(2–3), 720–30.
- Carrion, J. S., Riquelme, J. A., Navarro, C., and Munuera, M., 2001, Pollen in hyaena coprolites reflects late glacial landscape in southern Spain, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **176**, 193–205.
- Connolly, P., 1981, *Greece and Rome at war*, Greenhill Books, London.
- Cronk, J. K., and Fennessy, M. S., 2001, *Wetland plants: biology and ecology*, CRC Press, Boca Raton, FL.
- de Beer, Sir G., 1956, *Alps and elephants*, E. P. Dutton, New York.
- de Beer, Sir G., 1967, *Hannibal's march*, Sidgwick and Jackson, London.
- de Beer, Sir G., 1969, *Hannibal: challenging Rome's supremacy*, The Viking Press, New York.
- de Beer, Sir G., 1974, *Hannibal: the struggle for power in the Mediterranean*, Book Club Associates, London.
- Dodge, T. A., 1891, *Hannibal*, Houghton-Mifflin, Boston.

- Elliott, T. L., and Henry, G. H. R., 2011, Effects of simulated grazing in ungrazed wet sedge tundra in the high Arctic, *Arctic Antarctic and Alpine Research*, **43**, 198–206.
- Freshfield, D. W., 1886, The Alpine pass of Hannibal, *Proceedings of the Royal Geographical Society and Monthly Record of Geography*, **8**(10), 638–44.
- Freshfield, D. W., 1899, Hannibal's pass, *The Geographical Journal*, **13**(5), 547–51.
- Hart, B. H. L., 1967, *Strategy*, Faber and Faber, London.
- Kropf, M., Mead, J. I., and Anderson, R. S., 2007, Dung, diet, and the paleoenvironment of the extinct shrub-ox (*Eucatherium collinum*) on the Colorado Plateau, USA, *Quaternary Research*, **67**, 143–51.
- Kuhle, M., and Kuhle, S., 2012, Hannibal gone astray? A critical comment on W. C. Mahaney et al.: 'The Traversette (Italia) rockfall: geomorphological indicator of the Hannibalic invasion route' (*Archaeometry*, **52**, 1 [2010] 156–72), *Archaeometry*, **54**, 591–601.
- Lancel, S., 1999, *Hannibal*, Blackwell, Oxford.
- Lazenby, J. F., 1998, *Hannibal's war*, University of Oklahoma Press, Norman, OK.
- Leveau, P., 2007, Archeology and geoaerchaeology in the Alps: the paradigm of Romanization, *Geomorphologie*, **no. 1**, 85–98.
- Livy, 1965, *The war with Hannibal*, transl. A. de Séincourt, Penguin, London.
- Mahaney, W. C., 1990, *Ice on the Equator*, Wm Caxton Press, Ellison Bay, WI.
- Mahaney, W. C., 2002, *Atlas of sand grain surface textures and applications*, Oxford University Press, Oxford.
- Mahaney, W. C., 2004, Geological/topographical reconnaissance of Hannibal's invasion route into *Italia* in 218 BC, in *Studies in military geography and geology* (eds. D. R. Caldwell et al.), 67–78, Kluwer Academic, Dordrecht.
- Mahaney, W. C., 2008, *Hannibal's odyssey: environmental background to the Alpine invasion of Italia*, Gorgias Press, Piscataway, NJ.
- Mahaney, W. C., 2013, Comments on M. Kuhle and S. Kuhle (2012): 'Hannibal gone astray? A critical comment on W. C. Mahaney et al., "The Traversette (Italia) rockfall: geomorphological indicator of the Hannibalic invasion route" (*Archaeometry*, **52**, 1, [2010], 156–72)', *Archaeometry*, **55**, 1196–204.
- Mahaney, W. C., Keiser, L., 2012, Weathering rinds—unlikely host clasts for an impact-induced event, *Geomorphology*, **184**, 74–83.
- Mahaney, W. C., Kalm, V., and Dirszowsky, R., 2008a, The Hannibalic invasion of *Italia* in 218 BC: geological/topographic analysis of the invasion routes, in *Military geography and geology: history and technology* (eds. C. P. Nathanail et al.), 76–86, Land Quality Press, Nottingham.
- Mahaney, W. C., Kapran, B., and Tricart, P., 2008b, Hannibal and the Alps: unraveling the invasion route from the geological evidence, *Geology Today*, **4**(6), 223–30.
- Mahaney, W. C., Barendregt, R. W., Carcaillet, C., Tricart, P., Rabufetti, D., and Kalm, V., 2010a, Debris flow burial of ancient wall systems in the upper Po River valley, *Italia*, *Geology Today*, **26**(6), 209–15.
- Mahaney, W. C., Miyamoto, H., Dohm, J., Baker, V., Cabrol, N., Grin, E., and Berman, D., 2007a, Rock glaciers on Mars: Earth-based clues to Mars' recent paleoclimatic history, *Journal of Planetary and Space Sciences*, **55**(1–2), 181–92.
- Mahaney, W. C., Kapran, B., Kalm, V., Tricart, P., Blarquez, O., Milner, M. W., Barendregt, R. W., and Somelar, P., 2010c, Hannibal's invasion route: age-old question revisited with new scientific data, *Archaeometry*, **52**, 1096–109.
- Mahaney, W. C., Tricart, P., Carcaillet, C., Blarquez, O., Ali, A. A., Argant, J., Barendregt, R. W., and Kalm, V., 2010b, The Traversette rockfall: geomorphological reconstruction and importance in interpreting classical history, *Archaeometry*, **52**, 156–72.
- Mahaney, W. C., Allen, C. C. R., Pentlavalli, P., Dirszowsky, O., Tricart, P., Keiser, L., Somelar, P., Kelleher, B., Murphy, B., Costa, P. J. M., and Julig, P., 2014, Polybius's 'previous landslide': proof that Hannibal's invasion route crossed the col de la Traversette, *Journal of Mediterranean Archaeology and Archaeometry*, **14**(2), 1–20.
- Mahaney, W. C., Keiser, L., Krinsley, D. H., Pentlavalli, P., Allen, C. C. R., Somelar, P., Schwartz, S., Dohm, J. M., Dirszowsky, R., West, A., Julig, P., and Costa, P. J. M., 2013, Weathering rinds as mirror images of palaeosols: examples from the Western Alps with correlation to Antarctica and Mars, *Journal of the Geological Society*, **170**, 833–47.
- Mahaney, W. C., Milner, M. W., Sodhi, R. N. S., Dorn, R. I., Boccia, S., Beukens, R. P., Tricart, P., Schwartz, S., Chamorro-Perez, E., Barendregt, R. W., Kalm, V., and Dirszowsky, R. W., 2007b, Analysis of burnt schist outcrops in the Alps: relation to historical archaeology and Hannibal's crossing in 218 BC, *Geoarchaeology*, **22**(7), 799–818.
- Mahaney, W. C., Kalm, V., Dirszowsky, R. W., Milner, M. W., Sodhi, R. N. S., Beukens, R., Dorn, R. I., Dorn, R. I., Tricart, P., Schwartz, S., Chamorro-Perez, E., Boccia, S., Barendregt, R. W., Krinsley, D. H., Seaquist, E., Merrick, D., and Kapran, B., 2008c, Hannibal's trek across the Alps: identification of sites of geoaerchaeological interest, *Mediterranean Archaeology and Archaeometry*, **8**(2), 39–54.
- Mahaney, W. C., Allen, C. C. R., Pentlavalli, P., Kulakova, A., Young, J. M., Dirszowsky, R. W., West, A., Kelleher, B., Jordan, S., Pulleyblank, C., O'Reilly, S., Murphy, B. T., Lasberg, K., Somelar, P., Garneau, M., Finkelstein, S. A., Sobol, M. K., Kalm, V., Costa, P. J. M., Hancock, R. G. V., Hart, K. M., Tricart, P., Barendregt, R. W., Bunch, T.

- E., and Milner, M. W., 2016, Biostratigraphic evidence relating to the age-old question of Hannibal's invasion of Italy, II: chemical biomarkers and microbial signatures, *Archaeometry*, doi: 10.1111/arc.12228.
- Miola, A., Bondesan, A., Corain, L., Favaretto, S., Mozzi, P., Piovan, S., and Sostizzo, I., 2006, Wetlands in the Venetian Po Plain (northeastern Italy) during the last glacial maximum: interplay between vegetation, hydrology and sedimentary environment, *Review of Palaeobotany and Palynology*, **141**, 53–81.
- Moore, P. D., Webb, J. A., and Collinson, M. E., 1991, *Pollen analysis*, 2nd edn, Blackwell, Oxford.
- Neumann, J., 1992, Climatic conditions in the Alps in the years about the year of Hannibal's crossing (218 BC), *Climatic Change*, **22**, 139–50.
- Oyama, M., and Takehara, H., 1970, *Standard soil color charts*, Japan Research Council for Agriculture, Forestry and Fisheries, Tokyo, Japan.
- Polybius, 1979, *The rise of the Roman Republic*, trans. I. Scott-Kilvert, 215–29, Penguin, London.
- Proctor, D., 1971, *Hannibal's march in history*, Oxford University Press, Oxford.
- Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haffidason, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffman, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M., and Van Der Plicht, J., 2013, IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP, *Radiocarbon*, **55**(4), 1869–87.
- Savage, J. J. H., 1934, The manuscripts of Servius' commentary on Virgil, *Harvard Studies in Classical Philology*, **45**, 157–204.
- Schwörer, C., Kaltenrieder, P., Glur, L., Berlinger, M., Elbert, J., Frei, S., Gilli, A., Hafner, A., Anselmetti, F. S., Grosjean, M., and Tinner, W., 2014, Holocene climate, fire and vegetation dynamics at the treeline in the northwestern Swiss Alps, *Vegetation History and Archaeobotany*, **23**, 479–96.
- Seibert, J., 1993, *Hannibal*, 75–134, Wissenschaftliche Buchgesellschaft, Darmstadt.
- Sodhi, R., Mahaney, W. C., and Milner, M. W., 2006, ToF-SIMS applied to historical archaeology in the Alps, *Applied Surface Science*, **252**, 7140–3.
- Soil Survey Staff, 1999, *Soil taxonomy*, USDA Agricultural Handbook No. 436, Government Printing Office, Washington, DC.
- Taylor, J. C., 1991, Computer programs for standardless quantitative analysis of minerals using the full powder diffraction profile, *Powder Diffraction*, **6**, 2–9.
- Tricart, P., Schwartz, S., Lardeaux, J. -M., Thouvenot, F., and Du Chaffaut, S. A., 2003, Aiguilles-Col Saint-Martin, *Carte Géologique de la France*, 1:50000.
- Valsecchi, V., and Tinner, W., 2010, Vegetation responses to climatic variability in the Swiss Southern Alps during the Misox event at the early–mid Holocene transition, *Journal of Quaternary Science*, **25**(8), 1248–58.
- Walsh, K., 2005, Risk and marginality at high altitude: new interpretations from fieldwork in the Faravel Plateau, Hautes Alpes, *Antiquity*, **79**, 289–315.
- Walsh, K., Mocchi, F., and Palet-Martinez, J., 2007, Nine thousand years of human landscape dynamics in a high altitude zone in the southern French Alps (Parc National des Ecrins, Hautes-Alpes), *Preistoria Alpina*, **42**, 9–22.
- Wilkinson, H. S., 1911, *Hannibal's march through the Alps*, The Clarendon Press, Oxford.