The Mass Grave Project

Advancing Mass Grave Investigation Through an Interdisciplinary Program of Actualistic Taphonomic Research

Mickleburgh, H.L.; Procopio, Noemi; Bonicelli, Andrea; Ogbanga, Nengi; Sguazzi, Giulia; Gino, Sarah; van der Hulst, R.; Doro, Kennedy; Gocha, Timothy P.; Wescott, Daniel J.; Kootker, L.M.; Ammer, Saskia T.M.

DOI
10.1007/978-3-031-86308-0_8

Publication date
2025

Document Version
Final published version

Published in
Forensic Archaeology and New Multidisciplinary Approaches

Chapter 8
The Mass Grave Project

Advancing Mass Grave Investigation Through an Interdisciplinary Program of Actualistic Taphonomic Research

Hayley L. Mickleburgh, Noemi Procopio, Andrea Bonicelli, Nengi Ogbanga, Giulia Sguazzi, Sarah Gino, Rogier van der Hulst, Kennedy Doro, Timothy P. Gocha, Daniel J. Wescott, Lisette M. Kootker, and Saskia T. M. Ammer

Abstract The "Mass Grave Project" is an interdisciplinary program of taphonomic experiments simulating clandestine mass and single graves with human body donors at the Forensic Anthropology Center, Texas State University (FACTS). It aims to contribute to the development, testing, and validation of scientific methods for mass grave investigation, by increasing current knowledge and understanding of mass grave taphonomy. Specific objectives include, among others: refining remote and

H. L. Mickleburgh (✉)
University of Amsterdam, Amsterdam, NL & Forensic Anthropology Center, Texas State University, San Marcos, TX, USA
e-mail: h.l.mickleburgh@uva.nl

N. Procopio · A. Bonicelli
University of Central Lancashire, Preston, Lancashire, UK

N. Ogbanga
Northumbria University, Newcastle upon Tyne, UK

G. Sguazzi · S. Gino
University of Eastern Piedmont, Vercelli, Piedmont, Italy

R. van der Hulst
Netherlands Forensic Institute, The Hague, the Netherlands

K. Doro
Ohio State University, Columbus, OH, USA

T. P. Gocha · D. J. Wescott
Forensic Anthropology Center, Texas State University, San Marcos, TX, USA

L. M. Kootker · S. T. M. Ammer
Vrije Universiteit Amsterdam & Co van Ledden Hulsebosch Centre, Amsterdam, the Netherlands

P. M. Barone, WJ M. Groen (eds.), *Forensic Archaeology and New Multidisciplinary Approaches*, Soil Forensics, https://doi.org/10.1007/978-3-031-86308-0_8

ground-based detection methods and 3D documentation techniques, investigating the potential of biomolecular and microbial biomarkers for more precise and accurate postmortem interval and age-at-death estimation, studying DNA degradation and transfer between individuals in mass graves, and evaluating diagenesis and alteration of isotopic signatures of different human tissues. The project aims to generate recommendations for documentation, sampling, and analysis protocols, as well as develop advanced virtual reality simulation and training environments that can be used for testing scientific hypotheses as well as the training of investigators in mass grave excavation and documentation methods.

Keywords Mass Graves Investigation · Taphonomic Research · Forensic Archaeology · Geophysical Detection · DNA and Isotopic Analysis

8.1 Introduction

Modern mass graves often result from gross human rights violations, conflict, and social and political turmoil. These are not isolated incidents: every year, clandestine mass graves add to the millions of people who go missing due to human rights violations across the globe (Hamadeh et al. 2021; Human Rights Council 2020). There is an urgent humanitarian and legal need to search for and investigate these graves, identify the dead, and return their remains to their families (Klinkner and Smith 2020). Historic and prehistoric mass graves also occur in a large variety of spatiotemporal contexts, and while these generally do not require humanitarian and forensic attention, these contexts offer uniquely valuable insights into past human society and culture (Osterholtz 2015; Osterholtz et al. 2014).

Mass graves, whether of (pre)historic or forensic origin, present uniquely challenging contexts for archaeological excavation and interpretation. These sites are particularly complex because they hold the remains of multiple individuals, often exhibiting significant disarticulation and commingling of bodies and body parts (Haglund 2002; Jessee and Skinner 2005; United Nations 2016). As a result, identifying individual remains and documenting each body becomes a highly intricate task.

The arrangement of human remains and associated materials in mass graves is influenced by human actions and natural taphonomic processes occurring both during and after burial. Taphonomic processes encompass all factors that affect the preservation of an organism's remains post-mortem, such as weathering, fragmentation, human and animal activity, as well as decomposition processes like putrefaction, skeletonization, and disarticulation. These interactions between natural processes and human activities can significantly alter and bias the archaeological record.

Given the destructive nature of archaeological excavation, evidence in mass graves must be meticulously recorded to meet the standards required for various judicial mechanisms. This necessitates a high degree of expertise and specialized

training among professionals involved in the investigation of these sites (Haglund & Sorg 2002; Stodder 2018).

Decomposition in mass graves is thought to be distinct from single graves, because large numbers of bodies are placed to decompose in direct contact with each other (a "body mass"), with little or no soil in between (Barker et al. 2017; Haglund 2002; Mant 1950, 1987; Troutman et al. 2014). Decay in a body mass can lead to the formation of voids and mixing of body parts (particularly when bodies skeletonize). Factors like disturbance and robbing of graves in attempts to conceal crimes can lead to high rates of commingling of the remains. The commingling of individuals poses a significant problem when investigating mass graves, as it makes the reassociation and identification of individuals extremely difficult. Displacement and dissociation also confound the reconstruction of the sequence of events surrounding death and deposition, which in forensic contexts can be critical to corroborate or negate testimony (Dirkmaat and Adovasio 1996). Mass graves have also been linked to differential decomposition patterns. This phenomenon is characterized by differences in the degree of body decomposition throughout the grave, and even within individual bodies, and can present as relatively good preservation of bodies at the center of a grave paired with skeletonization at the periphery (Barker et al. 2017; Haglund 2002; Mant 1950, 1987; Troutman et al. 2014). Differential decomposition affects the ability to identify individuals and can be demanding of field archaeologists, because digging equipment, personal protective clothing, and even packaging materials need to be adapted to the condition of the remains. Moreover, it makes it hard to identify remains, affecting the recording and interpretation of data, as well as the lifting and transportation of bodies. Differences in the condition of remains can hamper visibility and make it difficult to maintain recording standards across the grave.

The lack of knowledge of what precisely happens in mass graves during body decomposition impacts all phases of archaeological research: from the search for graves to the planning of excavations, data collection, and interpretation of results. Robust and reliable remote methods of locating graves—or monitoring them in situ until the excavation is deemed safe—are critical. Geophysical methods provide non-destructive approaches for detecting anomalies that provide investigative leads to clandestine individuals and mass graves (Keenan et al. 2018; Knaub 2019). Studies on investigating the use of geophysical techniques for locating graves and monitoring human decay have mostly relied on proxies such as pigs (Novo et al. 2011; Pringle et al. 2020). Questions remain surrounding how geophysical anomalies vary with time as bodies decay, and how changes in soil properties correlate with measured geophysical signals. Similarly, it remains unclear which methods are more suitable at the different decay stages. In addition, due to financial and logistical restrictions and security issues, ground-based techniques (e.g., walking surveys, ground penetrating radar) are not always feasible. In such cases, remote sensing using aerial and satellite images could provide viable alternatives. Remote sensing relies on contrasts between the target and its surroundings, such as soil and vegetation disturbances. Decomposition can cause a variety of alterations in spectral reflectance signatures of soil and vegetation due to microbial activity and the release

of chemicals by the body (Keenan et al. 2018; Lang 2014; Usai et al. 2014). However, the relation between decomposition and spectral signatures is poorly understood, and there are currently no established criteria to detect (specific stages of) body decomposition. This means that despite the widely acknowledged potential of Remote Sensing for detecting mass graves, it remains underused (Kalacska et al. 2009; Kroker 2015; Leblanc et al. 2014; Raymond et al. 2014; Sandalinas 2015; Silván-Cárdenas et al. 2017, 2021; Son 2022; Wang et al. 2013).

The pressure of limited time and resources, combined with the need to collect and record evidence meticulously, means that documentation methods during excavation need to be efficient, reliable, and robust. Three-dimensional recording methods such as structure-from-motion photogrammetry or 3D laser scanning offer the potential to capture complex spatial data, in a rapid and increasingly low-cost manner. Nonetheless, 3D documentation is currently underutilized for deposits with human remains, both in traditional and forensic archaeological contexts (Beier and Rando 2016). For the wider adoption of such recording methods, it is important that their impact on field operations, in terms of time, costs, and required training and personnel is limited. Moreover, for their routine implementation in forensic practice and, if required, submission as evidence to a court of law, the reliability and repeatability of the data capture and post-processing of complex mass grave environments need to be demonstrated.

In practice, archaeological investigation of mass graves suffers from additional challenges. Because of limited resources, insufficiently or non-archaeologically trained personnel are often the first to respond to cases. Due to a variety of political and social pressures, they may begin to process the scenes. This can lead to inadvertent destruction of context and can hamper investigations. Affordable, realistic, and easily deployable training tools and programs are in critical shortage, and excavation and documentation practices vary considerably (Haglund 2002; Hanson 2016; Human Rights Council 2020; UNAMI/OHCHR 2018). Further challenges to mass grave investigation are posed by the need, in some cases, to quickly identify the deceased. Precise and accurate estimation of age-at-death, or the reliability of isotopic signatures obtained from buried remains, for instance, can be crucial to aid the identification of the deceased, as well as help to negate or corroborate testimonials and other evidence. Rapid developments in biomolecular and isotopic analysis methods provide potential new methods to assist identification. The reliability and accuracy of such methods must be tested and validated for use as evidence in court. Promising research on forensic omics and the development of the microbiome throughout body decomposition has found biomarkers that can potentially be used to develop age-at-death estimation techniques that are precise and accurate for all age groups and can be used on small/fragmented tissue samples, as well as shown great potential for refining postmortem interval (PMI) estimation. These methods could be particularly valuable in cases with large PMI ranges and/or fragmented or commingled remains (Mickleburgh et al. 2021; Procopio et al. 2018), but further validation research is needed to develop these methods for application in forensic

and humanitarian investigations (Bonicelli et al. 2022). Similarly, while isotopic analysis to establish the geographic origin of the deceased has been widely applied in forensic investigations to aid identification, it remains unclear precisely how decomposition and diagenesis affect the antemortem isotopic compositions of different body tissues (hair, nails, bone), and the effects of laboratory cleaning procedures on isotope signatures recovered from human tissues are not fully understood (Chesson et al. 2020; Kootker et al. 2020, 2023; Toxvaerd 2020).

8.1.1 Forensic Taphonomic Experimentation

The variety of challenges facing forensic and humanitarian investigation of clandestine mass graves can impede the possibility of developing new and improving existing scientific methods of analysis. Nonetheless, there is a need for continued development and testing of the reliability of scientific methods and techniques for forensic and humanitarian purposes. Human taphonomy facilities provide unique laboratories to conduct the experiments necessary to understand the dynamic taphonomic processes of the grave to develop and test new (and existing) methods. Actualistic taphonomic experiments provide the opportunity to study and monitor changes over time and allow the controlling of conditions and collection of data in a safe and secure research environment. The replication of experiments in different environments is important to evaluate the effects of location-specific taphonomic conditions on the results and help to distinguish differences related to individual variation from environmental taphonomic variables. Moreover, replication studies support the development of environment-specific recommendations for analyses and protocols and are vital to the development of the field (Pokines and Symes 2013).

Mass grave research using human body donors was first undertaken in 2013 at the University of Tennessee's Anthropology Research Facility (ARF) and includes a grave containing 24 individuals, one with six individuals, one with three individuals, as well as single graves and empty control graves (Blau et al. 2018; Corcoran et al. 2018). More recently, a project documenting two mass graves (one with three and one with six individuals), a single grave, and empty control graves was initiated at the Australian Facility for Taphonomic Experimental Research (AFTER) at the University of Technology, Sydney (Blau et al. 2018). To date, these research programs have demonstrated the utility of remote sensing and geophysical methods to detect mass graves, as well as the impacts of multiple decomposing bodies on the microbiome and soil biogeochemistry (Blau et al. 2018; Corcoran et al. 2018; Keenan et al. 2018; Knaub 2019). These studies have also emphasized the importance of the repeatability of results, examination of temporal dynamics, and replication in different environments. The latter is fundamental for testing the validity and reliability of methods.

8.2 The Mass Grave Project

The complexity of uncovering and recording evidence in mass graves, and reconstructing the events that led to their creation, inspired the development of the Mass Grave Project (MGP). The project is designed to examine taphonomic processes in small-sized mass graves and explore and test (new) methods of investigation of these contexts. The project includes a series of taphonomic experiments using willingly donated human bodies to simulate mass and single graves at the Forensic Anthropology Research Facility (FARF), the outdoor human decomposition research facility managed by the Forensic Anthropology Center at Texas State University. FARF is located in the Texas Hill Country, near San Marcos. Body donations studied at FARF are made to FACTS under the Texas Revised Uniform Anatomical Gift Act and are exclusively acquired through the expressed and documented willingness of the donors and/or their legal next-of-kin (Gocha et al. 2022).

Donors and/or their next-of-kin are aware that donations are used for taphonomic studies. The body donation program complies with all legal and ethical standards associated with the use of human remains for scientific research.

In May 2021, a small-sized mass grave with six body donors, a control mass grave without body donors, three individual graves, and one individual control grave were placed (Fig. 8.1). The environmental and taphonomic variables in these graves were monitored over the course of 18 months, after which the graves were excavated (November 2022). Upon excavation, the human remains were collected,

Fig. 8.1 Mechanical excavation of the experimental graves, at the Forensic Anthropology Research Facility, May 2021

sampled, and placed in a secondary mass grave in a commingled fashion for phase 2 of the experiment, which is focused on complex, commingled mass graves.

8.2.1 Experiment Design

The MGP project uses an actualistic methodology to replicate clandestine human graves. Actualistic studies control for chosen observational parameters and replicate taphonomic effects by reproducing assumed causal events in a relatively controlled situation.

The FARF is located in the central Texan hill country, and its terrain consists of shallow clay-rich soil overlying deposits of limestone with grassland punctuated by woodlands of primarily oak and cedar trees (Barnes et al. 2000). The FARF has a semi-humid climate with hot summers and moderate winters. Freezing is uncommon, occurring on average 36 days per year. Vegetation consists mainly of scrub bushes, ashe juniper, and Texas live oak trees. At FARF, the soils are relatively alkaline with high carbonate content and relatively low organic matter. Because of the high clay and rock content, the soils at the FARF have relatively low permeability to air and water movement (Carson 2000; Dixon 2000; Fancher et al. 2017; Gillham et al. 2003). Groundwater is located in a deep aquifer system. The average annual precipitation is 81 cm, but the region experiences frequent droughts and flash flooding.

Prior to the excavation of the grave pits, the area was mapped and photographed. Vegetation and soil samples were collected at the surface. Weather stations at FARF record weather conditions at 30-minute intervals. Aerial and geophysical surveys were conducted of the area before excavation to document initial (subsurface) landscape and vegetation conditions. Two pits measuring 2.5 by 3 m wide and 75 cm deep and four pits measuring 2 m by 60 cm and 75 cm deep were excavated by backhoe and recorded in 3D using structure-from-motion photogrammetry. The soil in the experiment area consists of Rumple-Comfort soil (Carson 2000), which is made up of gravelly loamy clay, and extends to 75 cm deep at the location of the graves and control graves. Baseline soil samples were collected at multiple depths during excavation, and at a distance of 10 m and 200 m from the pits. Six clothed body donors were placed in the mass grave in a fresh stage of decomposition, in direct contact with each other in an "unorganized" fashion. The position of the bodies upon burial and excavation was recorded in 3D. Simultaneously, three additional body donors were buried individually in the smaller pits. Soil probes were placed in the graves containing body donors, as well as in the control graves, to measure core and periphery soil temperature, conductivity, and moisture content. Soil samples of graves and control graves were taken at monthly intervals for the first three months, and every three months thereafter, using probes at multiple depths. Probe holes were plugged and marked following sampling, to monitor changes in stable isotopic signatures and microbial communities. Monthly geophysical surveys of all graves and controls were conducted, including ground penetrating radar and electrical

resistivity tomography. Unmanned Aerial Vehicles (drones) equipped with remote sensors (thermal and hyperspectral) were deployed every month, to collect data on landscape and vegetation changes.

Prior to placement, each body donor was scanned using computed tomography (CT), to obtain a record of the tissues of the body and to obtain 3D models of each body for the development of optimized 3D documentation methods and the virtual 3D training tool. Data on biological sex, height, weight, ancestry, eye color, place of residence, medical treatment, cause of death, date of death, and duration and temperature of body of storage were collected for each individual body donor. Bodies that had been autopsied or individuals who had undergone chemotherapy, radiotherapy, or prolonged antibiotics treatment within 6 months before death were excluded from the experiment as much as possible, due to the potential effects on decomposition and reduction of soft tissue (both bacterial and insect driven), and isotopic, proteome and microbiome signatures. Tissue samples (hair, nails, teeth, iliac crest bone, mid-shaft tibia bone, a fifth metatarsal, as well as swabs of the oral and rectal cavities, periocular swabs, skin swabs from different areas of the body, and muscle tissue) were collected before placement in graves, and again upon excavation of the grave.

Gross decompositional changes to the body were scored upon placement and excavation of the body donors following Megyesi et al. (2005), and indicators of gross decomposition were recorded in written descriptions and photographs during both stages of the experiment, allowing posthoc scoring according to other visual methods. Although the total body score PMI estimation method by Megyesi et al. (2005) has limitations when applied to buried bodies or in non-temperate climates, it remains widely used and understood, facilitating comparison with other studies.

8.2.2 Overview of the Project Research Pillars

The aims and objectives of the Mass Grave Project are organized within four research pillars: Detection, Documentation and 3D Visualization, Identification, and Education and Training.

Detection

Robust and reliable remote and non-destructive (i.e., without excavating) methods of locating mass graves are important as logistical restrictions and security issues can mean that land-based or destructive techniques are not always feasible or desirable options in mass grave investigations. The MGP monitors landscape/soil/vegetation changes throughout the experiments using remote sensing and ground-based geophysical techniques and evaluates the reliability of these methods to detect the presence of a mass grave with human bodies throughout different stages of decomposition.

Geophysical anomalies were measured throughout the experiment using different non-invasive geophysical techniques including electrical resistivity tomography, electromagnetic, self-potential, and ground penetrating radar for locating, to examine variation in signals with time after burial and evaluate the performance of each technique individually and in combination. Unmanned Aerial Vehicles (drones) equipped with remote sensors (thermal and multispectral) were deployed every month, to collect remote sensing data on landscape and vegetation changes.

Documentation and 3D Visualization

Due to their complexity in terms of a large "body mass," differential decomposition, disarticulation, and commingling of bodies and body parts, combined with time and resource limitations, the documentation of evidence in mass graves can pose a challenge. Digital 3D data capture and 3D visualization methods allow researchers to record complex spatial relationships to a high level of detail and provide options for posthoc analysis, as well as reconstruct events leading up to burial, or to simulate hypothesized sequences of events. The MGP uses photogrammetric 3D recording techniques to document experimental mass and single graves, both to examine alterations of human remains and evidence over time during decomposition, and to devise protocols for rapid and reliable 3D documentation of deposits with multiple commingled remains which can be efficiently and affordably implemented during investigations. This project tests the accuracy and precision of photogrammetric 3D recording techniques to rapidly, accurately, and reliably document complex mass grave deposits, and in particular, examines the impact of using these methods on the workflow of field operations. Minimal disruption of field operations is desirable for these methods to become widely adopted. The most reliable and time-efficient data collection and post-processing procedures for recording complex commingled deposits will be used to develop an open-access 3D documentation protocol.

Identification

For the continued development of forensic omics age-at-death and PMI estimation techniques, the MGP studies bone omics profiles and soil microbiome profiles before and after burial. For techniques based on the microbial communities in different parts of the body, swabs (oral, rectal, palm of the right hand, back of the neck, sole of the right foot) were collected before frozen body storage, after frozen storage, and again after excavation for DNA methylation analysis and Next Generation Sequencing. To study the effects of diagenesis and decomposition on the isotopic signatures of human tissues (hair, nails, bone), Sr-Pb isotope compositions were analyzed using thermal ionization mass spectrometry (TIMS) and multicollector-inductively coupled plasma mass spectrometry (MC-ICPMS) respectively of samples taken before burial and after excavation.

The MGP also explores the potential of using various human biological tissues (other than bone or teeth) for identification through DNA profiling in complex contexts such as mass graves or mass disasters. Traditionally, DNA extraction from human remains in advanced stages of decomposition focuses on hard tissues like bones and teeth, as these are believed to preserve DNA profiles more effectively over time. To investigate the viability of using soft tissues for DNA profiling, this study examined the degradation of DNA profiles in swab (oral, rectal, skin, periocular), nail, and muscle tissue samples from both single and mass graves. These samples were collected at three stages: fresh before freezing, fresh post-freezing, and decomposed after excavation. The study also looked for signs of cross-contamination between body donors within the mass grave.

Additionally, the impact of freezing on human DNA preservation was analyzed to evaluate the appropriateness of using frozen body donors in taphonomic experiments for genetic research. The study aimed to assess the completeness of genetic information obtained from swabs (skin, oral cavity, and rectum) taken at different stages: upon arrival at the human taphonomy facility, after freezing for periods ranging from 11 to 455 days, and after thawing before burial for 18 months. Post-burial DNA profiling was also performed on various soft tissue sampling sites, including skin, oral, periocular, and rectal swabs, nails, cartilage, muscles, and internal organs. The performance of these samples was then analyzed in relation to body decomposition, burial type (individual or mass grave), and the body's position within the mass grave.

The MGP also includes an explorative study into the effects of mass grave conditions on the preservation and recoverability of drug concentrations in different tissues. Producing an accurate drug exposure profile post-burial can assist in death investigations and the identification of unknown bodies in cases of a known history of drug use. The analyses targeted the nail of the first toe and muscle tissues, to examine tissues that are known to preserve differently during decomposition. Muscle tissue and toenail segments were analyzed to assess post-burial drug concentration profiles in the mass grave. Tissues were screened using two innovative methods: an LC-QTRAP-MS method that semi-quantitatively detects the presence of 500 substances and an LC-HRMS method that screens for over 2000 substances qualitatively. The results were compared to the medical histories of the deceased and examined for potential contamination due to mass grave conditions. The segmented analysis of the whole toenail provides a profile of antemortem drug exposure for multiple months before death, which can provide investigators with very valuable information on the deceased.

Education and Training

The complex taphonomic environment of mass graves, and the fact that the destructive process of excavation means evidence must be immediately recorded appropriately, requires a high level of training from investigators. Physical replication of mass graves for training purposes is severely limited by the amount of time and

resources needed to simulate the hazardous and physically and emotionally strenuous working conditions. However, 3D visualization techniques, especially those that provide (partly) immersive and interactive experiences such as Virtual Reality (VR) environments, could provide viable alternatives and are known to improve learning, memory retention, and motivation to learn and understand (ICRC Innovation Unit 2019; Krokos et al. 2019). They offer opportunities to simulate mass grave investigation and provide training in a safe and secure manner and can be disseminated rapidly and widely among stakeholders in need of training and capacity-building. Various studies have demonstrated that 3D virtual environments play an important role in spatial learning and can help improve stress management and mitigate "sensory overload" associated with humanitarian work dealing with gross human rights violations and conflict (Ashkenazi et al. 2021; Engelbrecht et al. 2019; ICRC Innovation Unit 2019; Koutitas et al. 2021; Pollard et al. 2020).

The data generated from the various components of the project—particularly Documentation and 3D Visualization—are being utilized to create 3D virtual training tools. These tools are intended for use by international humanitarian organizations involved in mass grave investigations as well as in university teaching programs. They provide interactive 3D representations of mass grave taphonomy and excavation, serving as visual aids to illustrate the complexities of retrieving evidence from contexts with multiple commingled remains.

The tools will feature various interactive modules designed to guide users through decision-making processes in the field. These decisions include excavation strategies informed by surface features, estimated grave size, number of bodies, information from informants, field surveys, and logistical or time constraints. The tools are being developed with sustainability and accessibility in mind, avoiding reliance on commercial hosting platforms or costly, cumbersome equipment. Instead, they are optimized for use on common devices such as desktop computers, laptops, tablets, and smartphones.

Because virtual training environments are highly scalable, repeatable, and support effective learning and memory retention, these tools offer significant advantages. They can be deployed in diverse contexts with fewer logistical challenges compared to traditional training methods, enhancing accessibility and impact.

8.3 Results to Date

At the time of writing, phase 2 of the MGP is still underway, with excavation of the secondary mass grave not yet completed. Analyses of the environmental and tissue samples collected in phase 1 of the project have been completed, and the first results of the analyses are described below.

The results of the geophysical analyses (electrical resistivity tomography [ERT], electromagnetics [EM], and ground-penetrating radar [GPR]) of the first six months of the experiment showed an initial increase in resistivity across all graves, attributed to soil aeration from disturbed soil, followed by a steady decrease in resistivity,

especially in the mass graves, as decaying bodies produced conductive leachates. This decline in resistivity was more pronounced in mass graves than in individual graves. EM measurements were found to be good at isolating anomalies associated with the presence of bodies in the soil in the first days after burial, while electrical resistivity was useful for longer timeframes. GPR profiles also consistently show distorted reflectors and hyperbolas indicative of ground disturbances and the presence of human remains, but were limited by the presence of rocks and site-specific geology. Quasi-3D resistivity models provided detailed imaging of these changes over time, allowing for better visualization of grave outlines and decomposition effects. Overall, the results indicate that ERT is a valuable tool for forensic investigations, particularly for locating graves and monitoring decomposition, with GPR providing supplemental data despite its limitations. The geophysical analyses were found to be effective for both individual and mass graves, with ERT proving especially reliable for tracking temporal changes linked to human decay (Doro et al. 2022a, b).

While the multispectral image data are still under analysis, preliminary thermal data (DJI Zenmuse XT2, 7.5–13.5 μm) results include a distinct heat signature of 3–4 degrees Fahrenheit difference between the mass grave and the control mass grave when measured immediately before dawn during months 3–6 of the experiment, related to greater heat retention of the grave in comparison to surrounding soils combined with warmth generated by active decomposition of the bodies during that time.

With regard to documentation, the MGP has focused on seeking affordable and efficient 3D recording procedures. We used a simple photogrammetry procedure for ground-based 3D recording of small-sized mass graves. While recording in situ evidence is the primary goal, processing the 3D models immediately and examining them in the field was found to assist excavation planning significantly. The models were processed with Agisoft Metashape, a commercially licensed software; however, future work will focus on developing protocols using common Free and Open Source Software packages to process models. Each photography round took on average 20 mins to complete, which meant coordinating the excavation team to cease all excavation work for during this time. Nonetheless, if planned well, this was found to lead to minimal disruption of field activities and did not significantly delay the scheduled time for excavation of the graves.

The results obtained by the omics analyses conducted on bones demonstrate clear differences between the pre-burial and the post-burial samples, as well as between individual and mass graves, highlighting the effectiveness of bone proteomics, metabolomics, and lipidomics in differentiating fresh and decomposed bones, as well as specimens originated from single and mass graves. First of all, proteins are less abundant in the decomposed bones in comparison with their pre-burial counterparts, especially for blood plasma proteins such as hamoglobin and hemopexin, and for muscle proteins such as actin and myoglobin, as expected due to the decomposition process and as previously found in other works (Procopio et al. 2018). On the contrary, metabolites such as amino acids and prostaglandins associated with inflammatory processes are more abundant in post-burial samples,

whereas metabolite intermediates involved in nucleotide degradation and bile acids are more abundant in pre-burial samples, reflecting the activation of autolytic and microbial decomposition processes post-mortem.

Interestingly, the inter-individual variability associated with differences such as health condition, drug use, medications, and lifestyle is lower between the individuals buried in the mass grave than in the individual burials, especially for the proteomic and lipidomic profiles. When comparing bone proteins in single and mass graves, blood plasma proteins such as coagulation factor IX, pigment epithelium-derived factor, and prothrombin, as well as bone extracellular matrix proteins like chondroadherin, collagen alpha-1, and Matrix Gla protein, are significantly more abundant in mass grave samples than in the individual graves samples, suggesting overall a slower decomposition rate in the former. In a similar way, specific metabolites such as amines and selected amino acids are also more abundant in the mass grave bones, while sugars—critical sources of energy for bacterial decomposers—are instead more abundant in the single grave samples, highlighting again the differences in the decomposition processes between these two burial scenarios.

The results obtained from the analysis of the soil microbial communities in single and mass graves reinforce what was previously found with the omics analyses of the skeletal remains, in that soil microbial populations in single graves are more diverse than those found in mass graves. Additionally, machine learning algorithms applied to such samples can correctly classify soil originating from either single or mass graves collected at the end of the 18-month experiment, with an accuracy level of 95%. The main bacterial species used for the prediction are *Conexibacter* spp., known to be involved in carbon cycling in soil environments, and *Streptomyces* spp., also well-known soil decomposers. In addition to classification analyses, soil microbial data have also been used to estimate post-mortem interval in forensic contexts; however, in cases like this one, it is more precise to refer to this as time since burial estimation. Given the limited understanding of microbial dynamics in mass grave environments, it is essential to investigate the applicability of this methodology in mass graves before its implementation in real scenarios. Results from the MGP indicate that time since burial can be determined with good accuracy in single graves, with a mean absolute error of 3.2 months over the 18-month study period. In contrast, the accuracy of predictions in mass grave contexts is reduced, with an increased error of 4.9 months. Notably, the prediction accuracy is particularly low during the first 10 months of the experiment, after which subsequent samples yield more consistent estimations up to 18 months. The presence of multiple bodies in the same grave in different layers, along with the varying decomposition processes they undergo and that were well documented with the omics approaches on the skeletal remains, is likely key factors contributing to decreased accuracy in time estimations based on soil samples. These complexities in decomposition dynamics may interfere with microbial community composition and its subsequent analysis, suggesting that more research is needed to refine methodologies for estimating time since burial in mass graves.

The pre- and post-burial human scalp hair, human bone (iliac and tibia), and tooth enamel and dentine samples, as well as environmental samples of vegetation

and soils, have been prepared for chromatographic separation for Sr and Pb isotope analysis. At the time of writing, the results are awaiting further analysis and interpretation. Based on previous individual grave and surface placement experiments at FARF, isotopic shifts are expected in the post-burial samples of the MGP donations compared to the pre-burial signatures. In this previous work, more densely mineralized elements (cortical tibial bone and tooth enamel samples) showed good recoverability of the pre-placement isotope signatures, while less densely mineralized samples (iliac bone) showed more susceptibility to diagenetic alteration. Hair keratin was found to be highly susceptible to diagenetic alteration, as well as sensitive to alteration during laboratory cleaning treatment (Kootker et al. 2020, 2023). A preliminary examination of the data suggests that the isotopic shifts in the bone samples within the MGP are relatively subtle. In contrast, despite employing a more optimal cleaning method, an initial assessment indicates that the biogenic Sr-Pb signatures in the keratin samples have been compromised by diagenetic processes. Further analysis of the MGP results will be used to substantiate what is known about the effects of the FARF burial environment on the preservation and recoverability of isotopic profiles. Importantly, the research will examine whether individual versus mass burial leads to differences in the recoverability of unaltered isotopic signatures.

The analysis of human DNA degradation in soft tissues revealed several key findings. The quality of DNA profiles progressively decreased from fresh to thawed and ultimately to decomposed tissue. Interestingly, the extent of DNA degradation did not correlate with the stage of gross decomposition observed during the excavation of the bodies, nor with the body's position within the grave. In fact, bodies in the mass grave exhibited higher levels of DNA preservation compared to those in individual graves, although the stage of decomposition in the mass grave was less advanced than in the individual graves overall. However, signs of DNA cross-contamination were observed in the mass grave due to the close proximity of bodies. The results also confirmed that freezing and burial led to a progressive loss of genetic information (Sguazzi et al. 2022; Gino et al. 2024). However, while freezing and burial led to DNA degradation, the research shows that personal identification can still be achieved by focusing on a variety of tissue samples. The results underscore the complexity of DNA preservation in mass graves and allow for preliminary recommendations to be made on identification procedures for mass victim contexts, including using swabs from various tissues, such as skin, oral, and rectal areas, as viable alternatives to traditional tissue and bone sampling due to their ease of collection. The research also highlights the importance of sampling as many tissue types as possible to maximize DNA yield, especially in challenging contexts like mass graves, and timely sample collection after the discovery of remains, to mitigate the effects of further decomposition on DNA quality. Additionally, training of disaster response personnel remains important to ensure procedures are followed and contamination is prevented (Sguazzi et al. 2024a, b).

The results of toxicology screening show that drugs such as amlodipine, ketamine (and its metabolite norketamine), caffeine, cotinine, lisinopril, paracetamol, morphine, desloratadine, duloxetine, and quetiapine were detected in toenail samples, indicating that these tissues effectively preserve drug profiles post-burial. In

several cases, there was a correlation between the drugs found in the nails and the known medical history of the individuals. Thus far, no indications of contamination between body donors in the mass grave were found. Segmental analysis of toenails reveals a timeline of drug exposure, which provides forensic investigators with valuable insights into the deceased's drug use before death. The next step involves analyzing the toenails using Matrix-Assisted Laser Desorption/Ionization Time-of-Flight (MALDI-TOF), a mass spectrometry technique used to identify proteins, peptides, and small organic compounds, to image the spatial distribution of these substances within the nail, creating a visual map of their locations to understand drug use over time. This will also provide a more detailed understanding of how substances are preserved and distributed in nails after burial.

As described above, the MGP experimental graves were recorded in 3D before placement of body donors, and sequentially after each donor. The same process was repeated upon excavation of the graves, in reverse, that is, after lifting each body. These photogrammetry models are very helpful in showing the differences between the initial body placement and the final condition and position of remains after 18 months of burial (Fig. 8.2). However, capturing such 3D "snapshots" using photogrammetry results in a static model of only surface geometry. To develop such data further for training and education purposes, the 3D data should serve to visualize the changes in condition and spatial configuration of remains and allow a degree of interaction with objects in the grave. Virtual reconstruction and animation methods allow recreation of the graves in a dynamic, interactive way. To tackle this, the full body post-mortem CT scans of the donors, which provide a detailed three-dimensional view of the body, were processed to create 3D models of skeleton and soft tissues unique to the individual. These models were then processed using techniques used in videogame character development, including remeshing, retopologizing, and rigging. This creates highly accurate and posable virtual representations of the donors, that can be positioned precisely as their bodies were placed in the graves (Fig. 8.3), resulting in a virtually reconstructed grave that is not merely static surface mesh, but a virtual space filled with virtual objects that can be manipulated, examined, and changed to test or visualize hypotheses. A major advantage of preparing the CT scan data in this way is that it allows visualizing the position of the skeleton when the bodies enter the graves fully fleshed. This initial data can then be compared to the final positions of the bones upon excavation (Fig. 8.4). Understanding how these transformations affect human remains and other evidence in mass graves is important to reconstructing the criminal actions involved in their creation. A better understanding of what to expect in mass graves of different ages, different numbers of individuals, and in different climates is also essential for planning of excavation of graves for legal or humanitarian purposes as well as protection of graves in situ. The virtual reconstructions from the MGP are still under development at the time of writing and will be developed further to contain additional detailed data on the physical changes of the grave over time, including information on differential human DNA degradation within the grave and how the microbiome of the grave changes over time. While these patterns can be visualized in 2D, incorporating them into a 3D virtual reconstruction helps to study, for

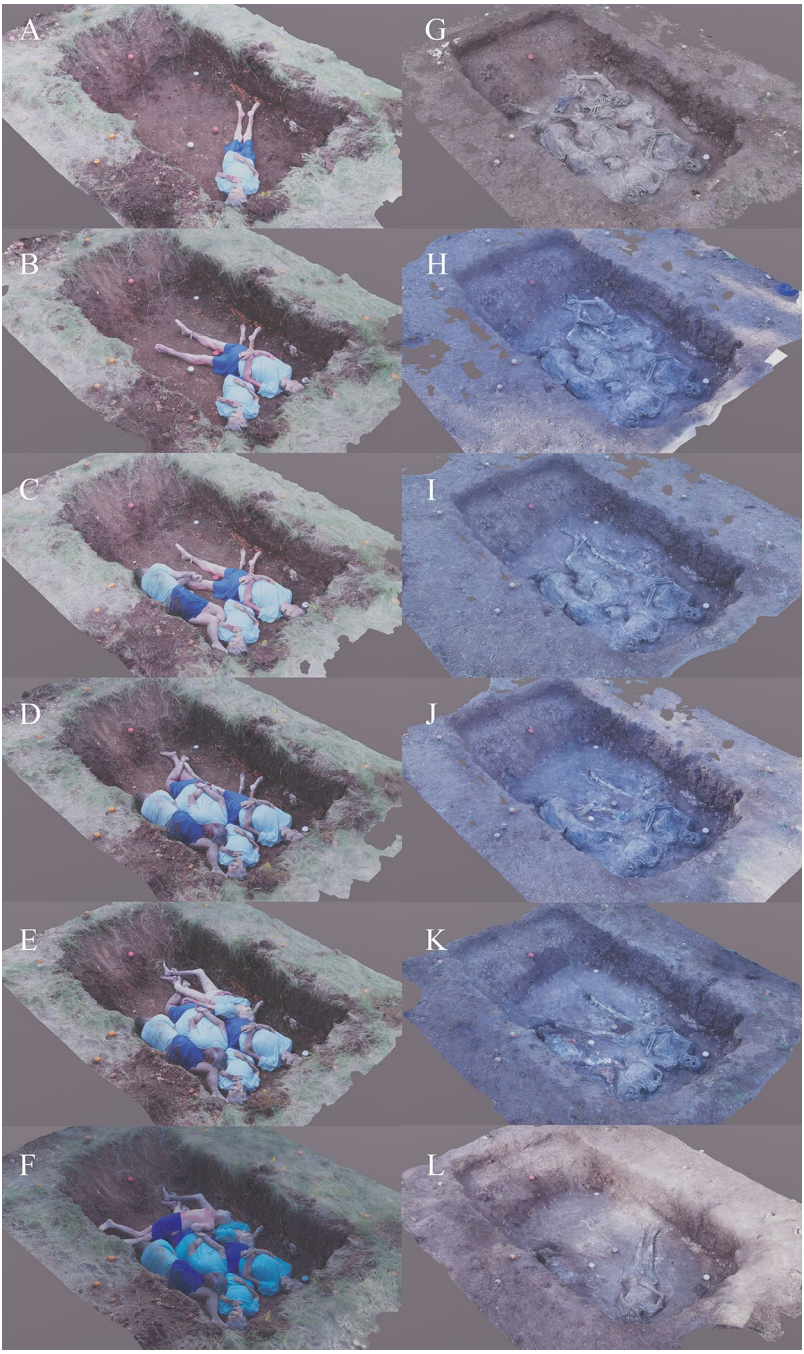

Fig. 8.2 Sequential 3D models of the experimental primary mass grave during placement (**a–f**) and during excavation and lifting (**g–l**)

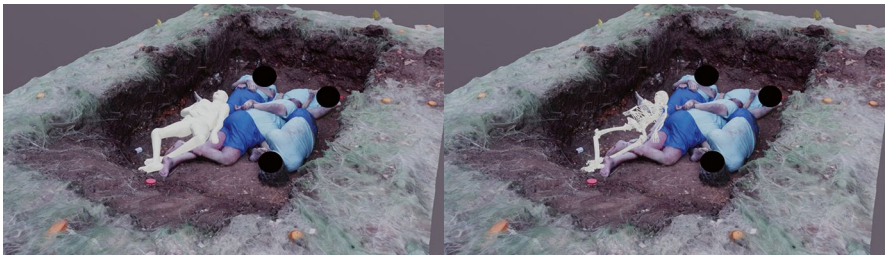

Fig. 8.3 Rigged and posed virtual body donor (white) placed in original burial position during the construction of the virtual mass grave. The Left shows the fleshed body donor, right only the skeleton

Fig. 8.4 Virtually reconstructed original position of the body donor's skeleton, overlaying the final position of the remains in the primary mass grave

example, how differences in the degree of human DNA degradation throughout the grave might be related to localized microbial variation. The virtual graves with all scanned bodies, objects, and representations of the stratigraphy layers and tool marks from digging, as well as the results from other pillars of the project, will thus be processed into realistic Virtual Reality (VR) tools to enhance training for mass grave excavations, in which the user can virtually re-excavate the grave, removing individual bones and objects, and receiving step-by-step instructions on documentation and sampling procedures. The VR will incorporate animations of changes in the graves over time to help learners to understand how evidence in the grave relates to the original conditions and spatial arrangement of bodies.

8.4 Discussion

The preliminary geophysical analysis of the graves during the first six months of burial indicated that there is a need for long-term studies to monitor the progression of electrical resistivity changes beyond six months to better understand how decomposition affects geophysical signals over time. The results of the geophysical surveys in months 7–18 of the project are currently under analysis and are expected to yield further insight into the long-term effects of decomposition on soil properties, the spatial spread of leachates, and the potential for distinguishing between individual and mass graves over extended periods. Nonetheless, more research is required to refine the application of geophysical methods in diverse soil types and environmental conditions, as the current limitations in GPR due to soil composition at FARF need to be addressed. Including more advanced 3D imaging techniques and multi-method approaches (e.g., combining resistivity with magnetic or seismic methods) could enhance detection accuracy. In addition, there is an important opportunity to explore automated data processing and interpretation methods, such as machine learning, to streamline forensic investigations using geophysical data. The remote sensing data collected throughout the MGP are the topic of a PhD project, which aims to develop and validate remote sensing techniques, including spectral and thermal imaging, to detect and monitor clandestine mass graves in conflict zones. This project will use the UAV-collected data (RGB, multispectral, and thermal imaging) alongside satellite imagery and develop machine learning algorithms to analyze these images to distinguish graves from other disturbances.

The innovative application and integration of omics analyses in the context of mass graves has generated valuable knowledge into the decomposition processes unique to mass grave scenarios. This molecular-level insight has contributed to laying robust foundations for the development of improved forensic methodologies for the study of human decomposition in mass grave contexts. The limits of some methods applied here, such as the post-burial estimation via soil microbiome analyses in mass grave contexts, underline the needs for more research on experimental mass graves. Such studies are essential to improve the understanding of the biological phenomena occurring in these complex circumstances, which in turn can inform improved sampling strategies for better forensic results.

The results of previous isotopic studies on the preservation and recoverability of isotopic signatures have emphasized that further research is needed into the effects of taphonomic processes, diagenesis, and cleaning protocols on isotope compositions of different human tissues often targeted in forensic investigations. The results of the MGP isotopic study will further evaluate and substantiate previous findings, while providing unique insights into how isotopic signatures preserve in mass grave environments.

The DNA results to date provide valuable insights into how freezing, burial, and advanced decomposition can substantially impact the integrity of DNA, thereby influencing genetic identification in mass grave contexts. These findings will be further developed into recommendations for forensic practice and future research in

challenging scenarios, such as mass graves and mass disasters, where cross-contamination and varying states of preservation often complicate the identification process. The research highlights the need for more refined genetic identification strategies tailored to complex contexts such as mass graves, where the risk of DNA degradation and cross-contamination is particularly high. Importantly, the results emphasize the necessity of multi-sample approaches, targeting different tissue types and sampling different locations on the body, to maximize the chances of successful identification.

The findings of the toxicology screening are encouraging, showing that significant drug profiles can be detected in nail long after burial. The detected drugs can contribute to human identification and help reconstruct the circumstances surrounding death, since exposure to certain drugs can reveal information about medical conditions, drug abuse, or poisoning. For example, the presence of cardiovascular drugs such as lisinopril may indicate high blood pressure or other heart-related diseases, while the presence of psychopharmaceuticals, such as duloxetine or quetiapine, can suggest psychiatric conditions. The toxicology results thus far do not appear to indicate that mass grave conditions hindered the detection of drug exposure from muscle or nail tissues, by comparison to individual grave conditions. However, further longitudinal studies that track drug degradation or persistence over longer post-burial periods are needed to substantiate these findings and to investigate how long drugs and their metabolites can remain detectable in various tissues under different burial conditions.

The development of 3D virtual reality training tools holds great potential for advancing both investigative and educational approaches to mass graves. Virtual graves not only aid in reconstructing taphonomic processes but also serve as dynamic archives for interdisciplinary data, supporting hypothesis testing and further analysis. They offer significant benefits for education and training, in particular, due to Virtual Reality's ability to enhance spatial memory and learning. Simulating real excavation conditions prepares trainees for the challenges of real investigations, including the impact of dealing with decomposing human remains. Moreover, their ability to be rapidly and remotely deployed is particularly advantageous in contexts with practical or financial constraints. A prototype of these tools will be tested within existing training programs used by international humanitarian organizations and among university students in Forensic Anthropology and Archaeology. Feedback from these users will be used to make modifications where needed.

8.5 Conclusion and Future Research

The Mass Grave Project, through the use of actualistic taphonomic experiments, has begun to shed light on the complex processes that occur in mass graves, contributing to advancements in both documentation and analysis techniques. A critical component of this research is the interdisciplinary approach, which recognizes mass graves as intricate archaeological and forensic contexts shaped by a variety of

interconnected factors. These factors include, among other thigs, local soil conditions, weather patterns, the number of individuals interred, and the specific methods used by perpetrators to dispose of the bodies. By integrating expertise from multiple fields—including archaeology, forensic taphonomy, biomolecular sciences, geophysics, remote sensing, 3D visualization, and virtual reconstruction—the MGP examines how these variables interact to affect the evidence. This interdisciplinary perspective is essential for identifying the most effective methods for investigating mass graves and for designing training programs that address the specific challenges presented by these contexts.

Phase 2 of the project, which began in November 2022 and is scheduled for completion in 2025, builds on the work of Phase 1 by simulating the scenario of secondary deposition following the disturbance of a primary grave. In this phase, donors from the primary graves have been reinterred in a commingled secondary mass grave. The precise position of each bone and body part was recorded in 3D during placement, and additional items, such as empty shell casings, beer bottles, and cigarette butts with human DNA, were also deposited in the grave. In addition to continuing the research pillars established in Phase 1, a key goal of Phase 2 is to enhance the methods used for excavating and recording commingled deposits. This will involve analyzing the decision-making processes of archaeologists and anthropologists who are unaware of the minimum number of individuals (MNI) or their positions within the grave. Another important aim is to determine whether DNA profiles and fingerprints can be recovered from the items placed in the grave, potentially providing further insights into the forensic recovery of evidence from mass graves.

Acknowledgments Foremost, our sincerest thanks go to the body donors and their next of kin, whose extremely valuable gift make crucial research into mass graves possible. We are also very grateful to the staff and students of the Forensic Anthropology Center at Texas State, Texas State University, San Marcos, Texas, for their continuing support for the Mass Grave Project.

We also gratefully acknowledge the advice and/or assistance of: Prof. Maurice Aalders, Prof. Roelof-Jan Oostra, Samantha De Simone, Adrienne Stainton, Casey Flint, Samantha.

Sawyer, Dr. Petra Banks, Shelbey Garza, Emma Giacomello, Dr. Deborah Cunningham, Dr. Paul.

Emanovsky, Dr. Devora Gleiber, Dr. Sophia Mavroudas, Heather Nesbitt, Dr. Lauren Meckel, Ivanna Robledo, Dr. Courtney Siegert, Amar Kolapkar, Efemena Emmanuel, Jessika Bentivogli, Wendell Geigle, Lotte Wever, Samuele Voyron, Veronika Pace, Akram Alkhomaisi, Sandra Sostaric, Nicole Lambacher.

Finally, we thank the funding organizations who supported this work: the Leiden University Fund Byvanck (Grant number 5604/30-4-2015/ Byvanck), the 2017 Royal Netherlands Academy of Arts and Sciences (KNAW) "National Postdoc Prize," the VINNOVA MSCA postdoctoral research project "THANATOS" (Grant number 2019-05211), and the European Meeting on Forensic Archaeology Best Presentation Award 2021. The DNA research conducted in the Mass Grave Project is the result of a study conducted in the framework of the International PhD in Global Health, Humanitarian Aid, and Disaster Medicine organized by University of Eastern Piedmont.

References

Ashkenazi I, Rapaport C, Kelling N, Izygon M, Buras W (2021) Stress management as key factor for enhanced first responder training: virtual reality at the service of life savers. J Emerg Med Services, 9 September 2021

Baier W, Rando C (2016) Developing the use of Structure-from-Motion in mass grave documentation. Forensic Sci Int 261:19–25

Barker C, Esma A, Santana JN (2017) Post-mortem differential preservation and its utility in interpreting forensic and archaeological mass burials. In: Schotsmans EMJ, Márquez-Grant N, Forbes SL (eds) Taphonomy of human remains: Forensic analysis of the dead and the depositional environment. John Wiley & Sons Ltd, Chichester, pp 251–276

Barnes PW, Liang S-Y, Jessup KE, Ruiseco LE, Phillips PL, Reagan SJ (2000) Soils, topography, and vegetation of the Freeman Ranch. Freeman Ranch Publication Series 1. Southwest Texas State University Press

Blau S, Sterenberg J, Weeden P, Urzedo F, Wright R, Watson C (2018) Exploring non-invasive approaches to assist in the detection of clandestine human burials: developing a way forward. Forensic Sci Res 3(4):304–326

Bonicelli A, Mickleburgh HL, Wescott DJ, Procopio N (2022) The 'ForensOMICS' approach for postmortem interval estimation from human bone by integrating metabolomics, lipidomics, and proteomics. elife 11:e83658

Carson D (2000) Soils of the Freeman Ranch, Hays County, Texas. Freeman Ranch Publication Series 4. Southwest Texas State University Press

Chesson LA, Meier-Augenschein W, Berg GE, Bataille CP, Bartelink EJ, Richards MP (2020) Basic principles of stable isotope analysis in humanitarian forensic science. In: Parra RC, Zapico SC, Ubelaker DH (eds) Forensic science and humanitarian action: interacting with the dead and the living. John Wiley & Sons, pp 285–310

Corcoran KA, Mundorff AZ, White DA, Emch WL (2018) A novel application of terrestrial LIDAR to characterize elevation change at human grave surfaces in support of narrowing down possible unmarked grave locations. Forensic Sci Int 289:320–328

Dirkmaat DC, Adovasio JM (1996) The role of archaeology in the recovery and interpretation of human remains from an outdoor forensic setting. In: Sorg MH, Haglund WD (eds) Forensic taphonomy: The Postmortem Fate of Human Remains. CRC Press, Boca Raton, pp 39–64

Dixon R (2000) Climatology of the Freeman Ranch, Hays County, Texas. Freeman Ranch Publication Series 3. Southwest Texas State University Press, pp 1–9

Doro KO, Emmanuel DE, Bank C-G, Wescott DJ, Mickleburgh HL (2022a) Time-lapse electrical resistivity tomography imaging of buried human remains in simulated mass and individual graves. Front Earth Sci 10

Doro, K.O., Kolapkar, A.M., Bank, C-G., Wescott, D.J., & Mickleburgh, H.L. (2022b). Geophysical imaging of buried human remains in simulated mass and single graves: Experiment design and results from pre-burial to six months after burial. Forensic Sci Int, 335, 111289

Engelbrecht H, Lindeman RW, Hoermann S (2019) A SWOT analysis of the field of virtual reality for firefighter training. Front Robot AI 6:101

Fancher JP, Aitkenhead-Peterson JA, Farris T, Mix K, Schwab AP, Wescott DJ, Hamilton MD (2017) An evaluation of soil chemistry in human cadaver decomposition islands: Potential for estimating postmortem interval (PMI). Forensic Sci Int 279:130–139

Gillham D, Young P, Long M (2003) Atlas of Freeman Ranch. Department of Geography, Texas State University

Gino S, Sguazzi G, McCarthy-Allen M, Colombo N, Wescott DJ, Gocha TP, Procopio N, Mickleburgh HL (2024) The Mass Grave Project: the impact of freezing and burial on personal identification through human DNA analysis. In: Proceedings of the 76th AAFS Annual Scientific Meeting, Denver, February 19–24, 2024, p 878

Gocha TP, Mavroudas SR, Wescott DJ (2022) The Texas state donated skeletal collection at the forensic anthropology center at Texas state. Forensic Sci 2(1):7–19

Haglund WD (2002) Recent mass graves, an introduction. In: Haglund WD, Sorg MH (eds) Advances in forensic taphonomy: method, theory, and archaeological perspectives. CRC Press, Boca Raton, pp 243–261

Haglund WD, Sorg MH (2002) Advancing forensic taphonomy: purpose, theory, and process. In: Advances in forensic taphonomy: method, theory, and archaeological perspectives. CRC Press, Boca Raton, pp 4–29

Hamadeh N, Decker A, McDonald-Gibson C, Cruz Santiago A, Baik T-U, Klinkner M (2021) Global report on Missing Persons 2021. International Commission on Missing Persons, The Hague

Hanson I (2016) Mass grave investigation and identifying Missing Persons: challenges and innovations in archaeology and anthropology in the context of mass death environments. In: Handbook of Missing Persons pp 491–514

Human Rights Council (HRC) (2020) Report of the Special Rapporteur on extrajudicial, summary or arbitrary executions. Mass graves, highlighting the multitude of sites of mass killings and unlawful deaths across history and the world. Retrieved from https://digitallibrary.un.org/record/3888738

ICRC Innovation Unit (2019) Review article: the current state of virtual reality on behavior change. Extended Reality & Behavior Change Series

Jessee E, Skinner M (2005) A typology of mass grave and mass grave-related sites. Forensic Sci Int 152(1):55–59

Kalacska ME, Bell LS, Sanchez-Azofeifa GA, Caelli T (2009) The application of remote sensing for detecting mass graves: an experimental animal case study from Costa Rica. J Forensic Sci 54(1):159–166

Keenan SW, Emmons AL, Taylor LS, Phillips G, Mason AR, Mundorff AZ, Bernard EC, Davoren J, DeBruyn JM (2018) Spatial impacts of a multi-individual grave on microbial and microfaunal communities and soil biogeochemistry. PLoS One 13(12):e0208845

Klinkner M, Smith E (2020) The Bournemouth protocol on mass grave protection and investigation. Bournemouth University, Bournemouth

Knaub MM (2019). Mass grave detection with the use of geophysics. Chancellor's Honors Program Projects. https://trace.tennessee.edu/utk_chanhonoproj/2302

Kootker LM, von Holstein ICC, Broeders J, Wescott DJ, Davies GR, Mickleburgh HL (2020) The effects of decomposition and environment on antemortem H-Sr-Pb isotope compositions and degradation of human scalp hair: actualistic taphonomic observations. Forensic Sci Int 312:110366

Kootker LM, Ammer STM, Wescott DJ, Davies GR, Mickleburgh HL (2023) Sr–Pb isotope differences in pre- and post-burial human bone, teeth, and hair keratin: implications for isotope forensics. Int J Legal Med 138:151

Koutitas G, Smith S, Lawrence G (2021) Performance evaluation of AR/VR training technologies for EMS first responders. Virtual Reality 25(1):83–94

Kroker P (2015) Satellite imagery as evidence for international crimes. International Justice Monitor blog. Retrieved from https://www.ijmonitor.org/2015/04/satellite-imagery-as-evidence-for-international-crimes/

Krokos E, Plaisant C, Varshney A (2019) Virtual memory palaces: immersion aids recall. Virtual Reality 23(1):1–15

Lang C (2014) The hidden archive of historical human inhumations locked within burial soils. PhD Diss. University of York

Leblanc G, Kalacska M, Soffer R (2014) Detection of single graves by airborne hyperspectral imaging. Forensic Sci Int 245:17–23

Mant AK (1950) A study in exhumation data [Doctoral dissertation, University of London]

Mant AK (1987) Knowledge acquired from post-war exhumations. In: Boddington A, Garland AN, Janaway RC (eds) Death, decay and reconstruction: approaches to archaeology and forensic science. Manchester University Press, Manchester, pp 65–78

Megyesi MS, Nawrocki SP, Haskell NH (2005) Using accumulated degree-days to estimate the postmortem interval from decomposed human remains. J Forensic Sci 50(3):JFS2004017

Mickleburgh HL, Schwalbe E, Bonicelli A, Mizukami H, Sellitto F, Starace S, Wescott DJ, Carter DO, Procopio N (2021) Human bone proteomes before and after decomposition: investigating the effects of biological variation and taphonomic alteration on bone protein profiles and the implications for forensic proteomics. J Proteome Res 20(5):2533–2546. https://doi-org.vu-nl.idm.oclc.org/10.1021/acs.jproteome.0c00992

Novo A, Lorenzo H, Rial FI, Solla M (2011) 3D GPR in forensics: Finding a clandestine grave in a mountainous environment. Forensic Sci Int 204(1–3):134–138

Osterholtz AJ (ed) (2015) Theoretical approaches to analysis and interpretation of commingled human remains. Springer

Osterholtz AJ, Baustian KM, Martin DL (eds) (2014) Commingled and disarticulated human remains. Springer, New York

Pokines J, Symes SA (eds) (2013) Manual of forensic taphonomy. CRC Press

Pollard KA, Oiknine AH, Files BT, Sinatra AM, Patton D, Ericson M, Thomas J, Khooshabeh P (2020) Level of immersion affects spatial learning in virtual environments: results of a three-condition within-subjects study with long intersession intervals. Virtual Reality 24(4):783–796

Pringle JK, Stimpson IG, Wisniewski KD, Heaton V, Davenward B, Mirosch N, Spencer F, Jervis JR (2020) Geophysical monitoring of simulated homicide burials for forensic investigations. Sci Rep 10:7544

Procopio N, Williams A, Chamberlain AT, Buckley M (2018) Forensic proteomics for the evaluation of the post-mortem decay in bones. J Proteome 177:21–30

Raymond NA, Card BL, Baker IL (2014) A new forensics: Developing standard remote sensing methodologies to detect and document mass atrocities. Genocide Stud Prevent 8(3):33–48

Sandalinas J (2015) Satellite imagery and its use as evidence in the proceedings of the international criminal court. German J Air Space Law 64(4):666–675

Sguazzi G, Mickleburgh HL, Ghignone S, Voyron S, Renò F, Migliario M, Sellitto F, Lovisolo F, Camurani G, Ogbanga N, Gino S, Procopio N (2022) Microbial DNA in human DNA extracts: recoverability of the microbiome in DNA extracts stored frozen long-term and its potential and ethical implications for forensic investigation. Forensic Sci Int Genet 59:102686. https://doi--org.vu-nl.idm.oclc.org/10.1016/j.fsigen.2022.102686

Sguazzi G, McCarthy-Allen M, Colombo N, Peroni G, Hayley MH, Wescott DJ, Gocha TP, Procopio N (2024a) Forensic genetics at the service of disaster victim identification: the preliminary results of the experimental Mass Grave Project. Book of Abstracts, 26th IALM Triennial Meeting, Athens, May 21–13, 2024, p 14

Sguazzi G, Peroni G, Colombo N, Mccarthy-Allen M, Mickleburgh HL, Wescott DJ, Gocha TP, Procopio N, Gino S (2024b) Recommendations for identifying disaster victims from the "Mass Grave Project": forensic genetics issues. Abstracts Book, 30th ISFG Congress, Santiago de Compostela, September 9–13, 2024, p 175

Silván-Cárdenas JL, Corona-Romero N, Madrigal-Gómez JM, Saavedra-Guerrero A, Cortés-Villafranco T, Coronado-Juárez E (2017) On the detectability of buried remains with hyperspectral measurements. In: Mexican Conference on Pattern Recognition. Springer, Cham, pp 201–212

Silván-Cárdenas JL, Caccavari-Garza A, Quinto-Sánchez ME, Madrigal-Gómez JM, Coronado-Juárez E, Quiroz-Suarez D (2021) Assessing optical remote sensing for grave detection. Forensic Sci Int 329:111064

Son SA (2022) Watching North Korea from the sky: Remote sensing and documenting human rights in The Democratic People's Republic of Korea. Polit Geogr 92:102525

Stodder AL (2018) Taphonomy and the nature of archaeological assemblages. In: Katzenberg MA, Grauer AL (eds) Biological anthropology of the human skeleton. John Wiley, Hoboken, pp 73–115

Toxvaerd S (2020) The strontium isotope ratio 87Sr/86Sr in archaeological organic matter conserved in acidic anaerobic environments is hard to interpret. J Archaeol Sci Rep 31:102379

Troutman L, Moffatt C, Simmons T (2014) A preliminary examination of differential decomposition patterns in mass graves. J Forensic Sci 59:621–626

UNAMI/OHCHR (2018) Unearthing Atrocities: Mass Graves in territory formerly controlled by ISIL. Report of 6 November 2018. Retrieved from https://www.ohchr.org/Documents/Countries/IQ/UNAMI_Report_on_Mass_Graves4Nov2018_EN.pdf

United Nations (UN), Human Rights Office of the High Commissioner (2016) Minnesota protocol: The Revised United Nations Manual on the effective prevention and investigation of extralegal, arbitrary and summary executions

Usai M-R, Pickering M, Wilson C, Keely BJ, Brothwell DR (2014) 'Interred with their bones': soil micromorphology and chemistry in the study of human remains. Antiquity 88:339

Wang B, Raymond N, Gould G, Baker I (2013) Problems from hell, solution in the heavens?: identifying obstacles and opportunities for employing geospatial technologies to document and mitigate mass atrocities. Stability 2(3):1–18