The development of a new geospatial framework for the palaeoanthropological site of the Sterkfontein Caves, Cradle of Humankind, Gauteng, South Africa

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Geographical Information Systems (GIS) provide an essential element in modern paleoanthropological inquiry through their ability to integrate a diverse range of data within a multidimensional spatial framework which can be used for data storage, analysis and modeling. One of the challenges of creating such a framework is the integration of legacy and new data (collected with digital technologies) at large sites with a long history of research. The Sterkfontein Caves, located in the Cradle of Humankind, is the richest *Australopithecus*-bearing locality in the world and has been the focus of intense palaeoanthropological research for the past 80 years. A diverse range of spatial data has been collected over this history and future integrative research necessitates the development of a unified, cohesive 3D GIS framework. In this paper we describe three phases of work undertaken to implement such a framework and discuss the next steps in its development and utilization for spatial analyses.

Keywords: Sterkfontein Caves, GIS, spatial analysis, hominin, *Australopithecus*, 3D

Introduction

The dolomite caves of the Cradle of Humankind have yielded some of the most important palaeoanthropological evidence in the world, and remain one of the most prolific palaeoanthropological areas. The Sterkfontein Caves, the richest repository of *Australopithecus* fossils in the world, is situated 50 km northwest of Johannesburg in the Blaaubank River valley, South Africa (FIG. 1). This valley is located in the southernmost area of the Cradle of Humankind and is of exceptional palaeoanthropological value as it also hosts the sites of Kromdraai, Swartkrans, Cooper's Cave and Bolts Farm—sites that document over three and a half million years (Granger *et al.* 2015) of landscape, faunal, environmental and hominin evolution. The deep caves of the Cradle of Humankind formed in the 2.6 Ga dolomitic limestone of the Malmani Subgroup (Eriksson *et al.* 2001; Martini *et al.* 2003). The extensive fossil- and artifact-bearing deposits accumulated within the Sterkfontein Caves have been subject to complex depositional and post-depositional processes creating particularly complicated stratigraphic histories and associations (e.g., Bruxelles *et al.* 2014, Stratford *et al.* 2012, 2014).

Research at the Sterkfontein Caves has continued since 1936 following the discovery of the first ever adult *Australopithecus* specimen, TM1511 (Broom 1936). The first part of this specimen, the brain endocast, was found in a mining spoil heap created through the quarrying of calcium carbonate speleothem deposits exposed on the landscape surface. The erosion of the landscape (and consequent removal of the roof) and quarrying of the surface-exposed speleothems revealed large areas of previously interred fossiliferous cave deposits which yielded many of the early hominin fossils including StS 5 (Ms. Ples) and the first partial *Australopithecus* skeleton StS 14 (Broom *et al.* 1950) (FIG. 2). This area is known as the 'Type Site' (TS in figures). In preparation for dedicated in situ controlled excavations of the surface-exposed sediments under the direction of Philip Tobias and management of Alun Hughes in 1966 (Tobias and Hughes 1969), Tobias initiated a comprehensive study of the Sterkfontein area including a geological investigation of exposed chert and oolitic beds (Bloom and Arvanitakis personal communication, 1968), a topographic survey (Watt personal communication, 1969), a vegetation study (Mogg 1975) and an aerial survey from Kromdraai to Sterkfontein. Excavations

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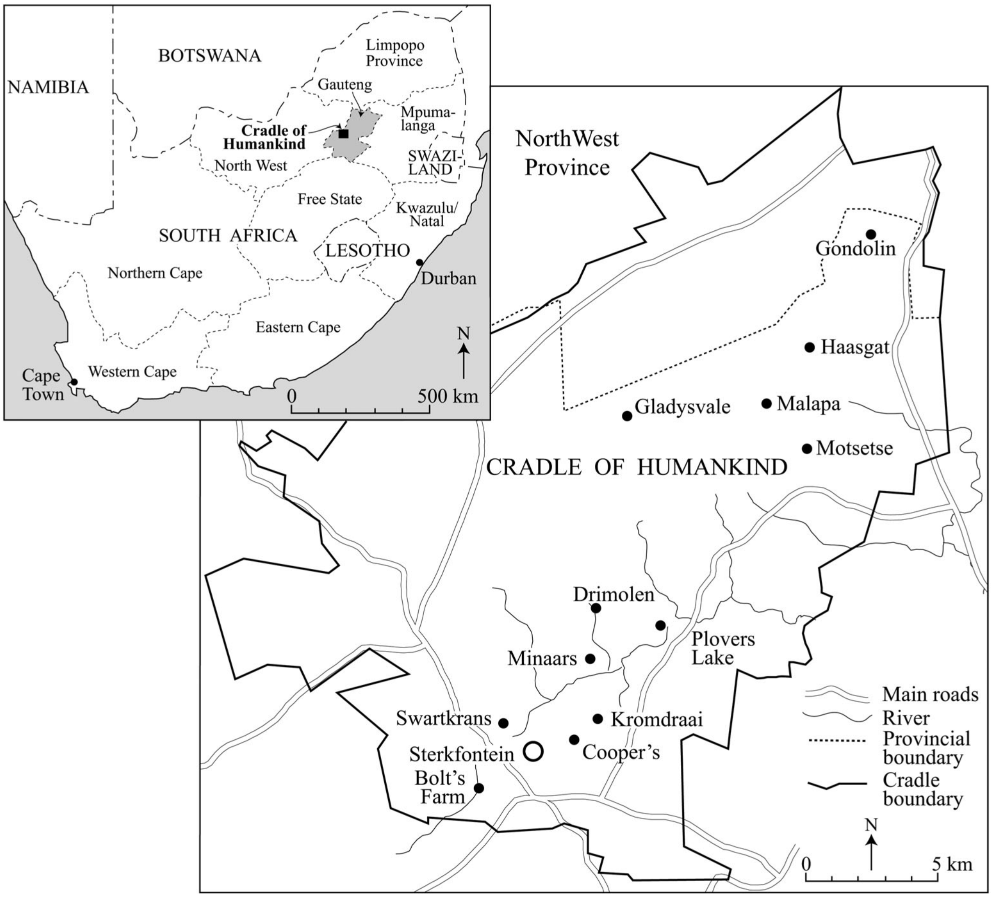

Figure 1 The Sterkfontein Caves and other key fossil sites in the Cradle of Humankind, South Africa.

Figure 2 The view west across the Sterkfontein excavation site. The reddish sediments are calcified fossiliferous cave deposits. The 'Type Site' area of Member 4 is located to the right beneath the walkway. In the distance, on the facing hillslope, is the site of Swartkrans (Photograph by D. Stratford).

were to commence from the western end of the site, an area now known as the 'Extension Site' and Revil Mason was consulted on excavation procedures (Mason personal communication, 1966).

On the 4th of July 1967, Watt and Mason began surveying an extensive excavation grid which has been used to this day as the primary framework for spatial control for all excavations of the surface-exposed breccias. The metal grid (still visible today) is suspended above the site and divides the surface excavation area into squares of one yard by one yard (3 feet). The grid is orientated at a bearing of 77° (Watt 1969; Tobias and Hughes 1969) with an origin at the north-east extremity of the site and square numbers increasing west (1–84) and letters increasing south (A-Xx) (FIG. 3). The primary depth datum (labeled 'old 'Z' datum' in figures) was located at the highest point of the site just to the southwest of the Type Site. Depth has been recorded in feet and inches below the datum. Generally, units were excavated in squares (1 yard by 1 yard; 3 feet by 3 feet; 91.44 sq cm) in arbitrary horizontal slices ('spits') of one foot (12 inches; 30.48 cm). For example, StW 563 was found in grid square Q50 within a spit depth of 17′11″ to 18′11″ below datum.

The reconciliation of the traditional comparatively low resolution fossil provenience data and the new high resolution total station generated provenience data was a key challenge during this project and is discussed below. Broader deposit boundaries or culturally defined assemblage distributions have been generally identified by the bounding grid squares and depths. For example, fossils or artifacts from the Member 5 East Oldowan deposit occupy an area between grid lines 49 to 58 and lines P through T between depths of 22′ to 36′ 10″ (Kuman and Clarke 2000) (FIG. 3). Excavations have attempted to limit the removed volumes of breccia and sediment to $3' \times 3' \times 1'$, but this can be problematic due to the heavy-duty methods often required to break the heavily calcified sediments into manageable blocks (e.g., mining drills and wedges).

Over the last five years, a new phase of dedicated stratigraphic work has commenced with more detailed, multidisciplinary stratigraphic approaches carried out across the Sterkfontein cave network (Bruxelles *et al.* 2014; Stratford *et al.* 2012, 2014). The goal is to more clearly understand the faunal and stratigraphic associations of the hominin material in light of, amongst other things, higher resolution investigations of palaeoenvironmental context and intra-species variation which are particularly pertinent given Clarke's identification of two co-existing species of the *Australopithecus* genus (see Clarke 2013 for review). Specialist studies have not yet been unified under a single spatial framework. Such a system is of particular importance for understanding the spatial associations of the excavated surface-exposed deposits Member 4 (M4) and Member 5 (M5). M4 has yielded the majority of the >750 *Australopithecus* fossils, including important hominin specimens like TM 1511, StS 5, StS 14, StS 71, StW 505 and StW 431 and are associated with a vast faunal assemblage and the only example of fossil wood recovered from the Cradle of Humankind sites (Bamford 1999). To the west of M4 is an important area for the understanding of the evolution of the earliest technology in South Africa called Member 5 (FIG. 3). Member 5 is divided into two units. A lower and larger deposit called M5 East has yielded the largest and most complete Oldowan assemblage in Southern Africa (Kuman and Clarke 2000; Kuman and Field 2009). Above and to the west of M5 East, an upper early Acheulean-bearing deposit named Member 5 West has been identified. The Member 5 (M5) deposits lie to the west of the main M4 excavation (FIG. 3) with an unconformable and complex deposit contact which is difficult to model 30 years after the excavation of this area began.

New excavations in the deep underground deposits have yielded some exceptional and very old hominin material, including the near-complete skeleton of StW 573 'Little Foot' (Clarke 1998), well-preserved cranial and post-cranial fossils from the Jacovec Cavern (Partridge *et al.* 2003; Granger *et al.* 2015) and the first hominin fossils from the Milner Hall (Stratford *et al.* 2016). Their stratigraphic histories and associations to the other hominin-bearing deposits are complex (Wilkinson 1983; Partridge and Watt 1991; and see Pickering and Kramers 2010 for recent alternative) and require detailed studies with high spatial resolution in order to reconcile the complex 3D sedimentary associations within the cave network. Figure 3 shows the spatial association of these underground chambers in relation to the upper, surface-exposed deposits. The geometry of the underground passages and chambers are currently derived from traditional cave mapping techniques involving compasses, tape measures (or laser distance meters) and inclinometers.

In order to aid the ongoing high resolution, multidisciplinary stratigraphic studies, in both excavated surface excavations and un-sampled areas of the subterranean chambers of the cave system, a unified geospatial framework with a potential for high resolution three dimensional modeling is clearly needed. Further, the unified geospatial system has to allow the integration of data from ongoing high resolution and multidisciplinary research with data from 70 years of previous studies and almost 50 years of excavation. Here we describe our work to establish a new geospatial framework at Sterkfontein in order to facilitate high resolution mapping, spatial modeling and analysis of multigenerational and multidisciplinary (legacy) data

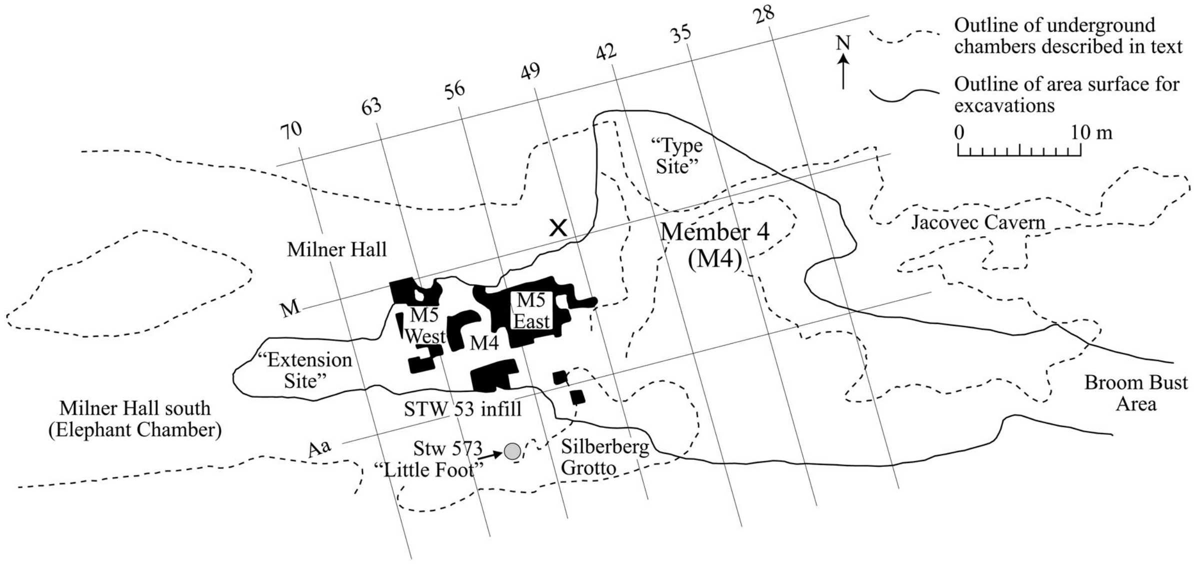

Figure 3 Plan view of the Sterkfontein surface excavation and grid established by I. Watt in 1967. Dashed lines represent the outlines of subterranean chambers mentioned in the text (modified from Kuman and Clarke 2000; Martini *et al*. 2003; Pickering and Kramers 2010; Reynolds and Kibii 2011). Outlines of subterranean chambers are derived from traditional speleological maps. The 'X' on the figure marks the location of the old 'Z' datum referred to in text.

and provide support for future investigations anywhere in the cave system. We also present an initial utilization of the framework in modeling the distribution of 649 'StW' prefixed hominin specimens by body part.

Methods

Spatial control was established through three phases and customized in accordance to requirements for the Sterkfontein site. The goal was to provide accurate ground control over the surface excavations first and then to extend the control network into the five kilometers of underground passages that make up the caves, particularly those areas which have been extensively researched or are the focus of new research (i.e., the Silberberg Grotto, the Milner Hall and the Jacovec Cavern).

Phase 1

The initial phase of establishing ground control on the surface excavation was to identify a single datum that would be used as a global reference anchor for all subsequent control points. This control point was named STK PCD1 (Sterkfontein Primary Control Datum 1). An old 32 mm mining wedge securely embedded in a massive dolomite block in the southern area of the heavily calcified Member 4 was chosen.

The global position of STK PCD1 was measured using a Spectra Precision EPOCH 50 L1/L2 GNSS Receiver with Ranger 3XC Controller and SurveyPro field software (TABLE 1). The Spectra Precision EPOCH 50 was set-up as a NTRIP Rover, with real-time connection to the South African TRIGNET System via an integrated GSM modem. TRIGNET is a network of permanent continuously operating GNSS base stations, distributed throughout South Africa at approximately 100–300 km spacing. All stations record one second epoch data on both GPS frequencies (L1 and L2) via geodetic standard choke ring antennas. Data from all stations is continuously streamed to the TRIGNET control center in the office of the Chief Directorate: National Geospatial Information from

Table 1 Locational data for the STK PCD 1 datum.

STK PCD1	
IRTF 2008 (Epoch 2012.01) Geographical Coordinates	
Latitude: 26° 00'26.55956''	
Longitude: 27° 44'04.90949''	
Altitude (WGS 84 Ellipsoidal Height): 1509.568 m	
South African Lo (Plane) Coordinates	
Central Meridian 27° E	Projection: Transverse Mercator
Grid Type: South West	Datum: Hartebeesthoek 94
Ellipsoidal Model: WGS 84	Geoid Model: South African Geoid 2010
Y: -73 547.655	X: 2 878 781.999
Orthometric Height: 1 493.622	

where it is made available in RINEX (Receiver Independent Exchange) format for post-processing as well as RTCM (Radio Technical Commission for Maritime services) format for real-time applications.

Once the position of STK PCD1 had been established, five other Primary Control Points (PCDs) extending over the surface excavation were identified and surveyed using a Spectra Precision FOCUS 8 Mechanical Total Station. The survey was based on the South African Lo (Plane) with the coordinates of STK PCD1 and orientation obtained from the initial survey. The five new PCDs were surveyed from at least three other PCD points to check and determine final coordinates in a local survey network. Calculations and accuracies achieved can be found in Online Supplement 1 (http://dx.doi.org/10.1080/00934690.2016.1157679). PCDs were located at strategic locations to allow a broad perspective over all areas of the open excavation while ensuring that at least two known PCDs are visible from anywhere in the excavation or other PCDs. Figure 4 shows the position of all PCDs, the outline of the excavation and the permanent walkways that extend over the site.

Phase 2

The second phase of the project involved extending control throughout the underground cave network (FIGS. 4, 5). This presented significant challenges as the passages are frequently small and intricate (FIG. 6). In order to ensure accuracy of the underground survey, three survey traverses were identified. Traverse A established datums A1-10 (FIGS. 4, 5) (Online Supplement 2: precision 1: 13 264; see http://dx.doi.org/10.1080/00934690.2016.1157679) and worked from PCD4 through the Silberberg Grotto exiting the chamber to the left and ascending to the surface via the tourist route where the traverse was closed. Traverse B established datums B1-16 (FIGS. 4, 5) (Online Supplement 3: precision 1: 31 534; see http://dx.doi.org/10.1080/00934690.2016.1157679) and follows, in reverse, the tourist route—that is from PCD2 down past the Broom bust and fossil chamber through the small central passages and Tuff Chamber into Milner Hall and back up the tourist route stairs where the traverse was closed with datum A7. Traverse C established datums C1-11 (FIGS. 4, 5) (Online Supplement 4; see http://dx.doi.org/10.1080/00934690.2016.1157679) and represents small traverses from Traverse B datums and incorporates the Jacovec Cavern and Milner Hall western extremities. Coordinates for each datum and accuracies for these traverses can be found in Online Supplements 2, 3 and 4 (see http://dx.doi.org/10.1080/00934690.2016.1157679). The accuracy of all traverses obtained a 1st class survey rating.

Phase 3

The third phase focused on providing synchronization between the new geospatial framework and the old grid system (i.e., the old physical grid established by Watt in 1968 [Tobias & Hughes 1969]). Linking the old grid system (the resolution of which is described above) with the new geospatial framework is of the utmost importance, given that the wealth of fossils excavated over the last 48 years is spatially identified through grid square and spit depth information. The possibility of analyzing the spatial organization of fossil assemblages in detail and in association to new stratigraphic and geochemical data can be enhanced by the use of a GIS-based system that exploits the three-dimensional locational information provided by the grid and spit provenience system implemented at Sterkfontein.

Although the spatial resolution of the legacy data derived from the old grid system may be considered low (fossils are identified by a common spit-unit provenience with a maximum resolution of $3 \times 3 \times 1$ ft), relative to total station or laser scanner surveyed data, it is nonetheless sufficient for a series of important and informative analyses when appropriately utilized in a digital environment. The benefits (and issues) of a 3D GIS-based spatial study of excavations have been discussed by a number of authors (Barceló *et al*. 2003; Harris and Lock 1996; Katsianis *et al*. 2008; Lieberwirth 2009; Merlo 2010). Nigro and colleagues (2002, 2003) explored the advantages of a digital environment to study hominin fossils at Swartkrans. These range from the ability to view and rotate 3D elements in space, query attribute data of specimens, statistically interrogate them and link them to associated faunal assemblages and geological contexts.

We are, therefore, constructing a site-wide GIS platform with a 3D environment in mind. So far, we have reconstructed the old excavation grid within a virtual metrically calibrated space, and modeled the distribution of part of the large M4 hominin assemblage within that framework (FIGS. 7, 8).

Applications

Creation of the Sterkfontein 2D virtual grid

The traditional physical grid was surveyed from the established PCDs using the National Grid system which is defined by a variation of the Transverse Mercator projection called the “Gauss Conform Projection”. This coordinate system is used in the Southern Hemisphere only and is based on a system of Westings (Y), measured from the central meridian (Lo) of the grid zone and Southings (X), measured southwards from the equator, instead of northings (N) and Eastings (E), which are the reference axes for Northern hemisphere projections and grid

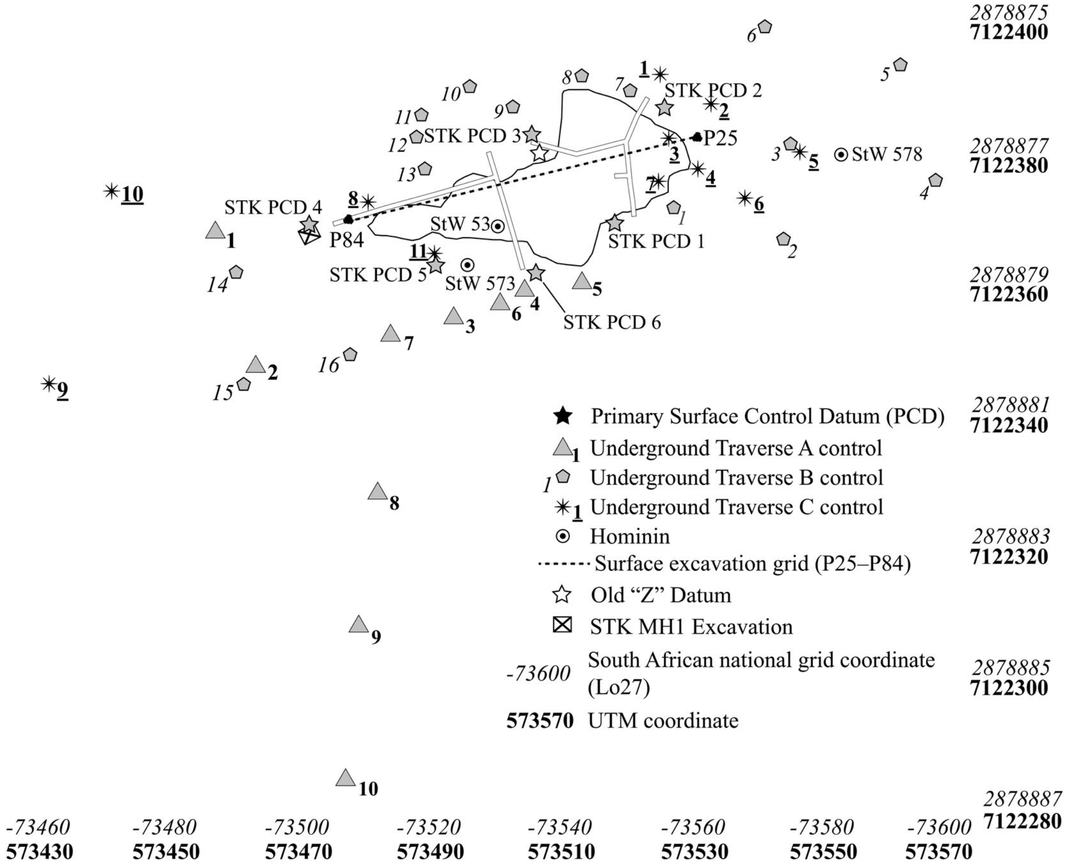

Figure 4 Plan view of the Sterkfontein surface excavation, Primary Control Datums (PCDs) and underground control points (Traverses A, B and C). Note the relative location of StW 573, the near complete *Australopithecus* skeleton (Clarke 1998) and StW 578, the *Australopithecus* cranium found in the ceiling of the Jacovec Cavern (Partridge *et al.* 2003). This accurate spatial association between the base level (lake level in Figure 5), subterranean and surface-exposed deposits is essential for understanding the infilling sequences and stratigraphic features relating to factors like cave development, geomorphology, erosional episodes, opening position and sediment flow directions across the extensive, multi-level cave network (see also in Figure 3). These aspects of research have been particularly problematic in the past (see Wilkinson 1973, 1983; Partridge and Watt 1991 and Pickering and Kramers 2010 for discussion).

systems (Parker 2012). These coordinate zones are referred to as Wg17, Wg19, Wg21 …etc. (Haartebeesthoek 1994 datum) since 1999, when the national system changed from one based on the Clarke 1880 modified ellipsoid to the more internationally recognized WGS84 ellipsoid (Parker 2011).

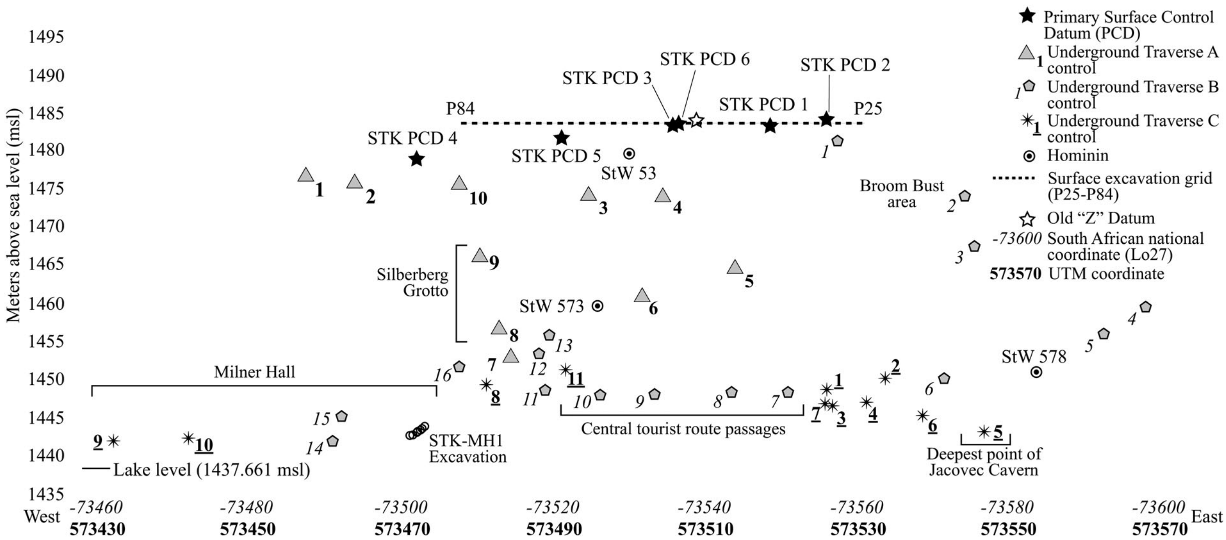

Figure 5 North facing X, Z aspect of the Sterkfontein Primary Control Datums (PCDs) and underground control points (Traverses A, B and C). Well known areas of the cave are labeled.

Figure 6 Surveying the lower underground passages of the Sterkfontein Caves. Here S. Brown is surveying datum 11 from datum 10 of Underground Traverse B (FIGS 4 and 5). This is part of the tourist route through the caves. Traverse C established datums away from the tourist accessible areas.

In the South African coordinate system, which is based on Y and X, y coordinates increase positively to the West and x coordinates increase positively to the South. This is different from the standard UTM system which is based on x and y, where x increases positively to the East and y increases positively to the North. To accommodate for this difference, in an unprojected system it is necessary to modify the values as follows, in order to visualize the data in their correct relative position:

$$\begin{aligned} \text{Xvalue (UTM)} &= \text{Y value (SA)} \times (-1) \\ \text{Yvalue (UTM)} &= \text{X value (SA)} \times (-1) \end{aligned}$$

Although the relative position and direction to the true north would be correct, the data created in such manner would be un-projectable and therefore incompatible with any other coordinate system such as, for example, WGS84 longitude and latitude (Mitchell 2011).

ArcGIS 10.1 was chosen as the software to create the 2D excavation grid. Differently from other GIS software, ArcGIS supports both the old and the new South African datum and possesses information on transformation parameters to different projections and coordinate systems. Two grid points from the old system were used as references to establish the virtual grid which was created using the ArcGIS

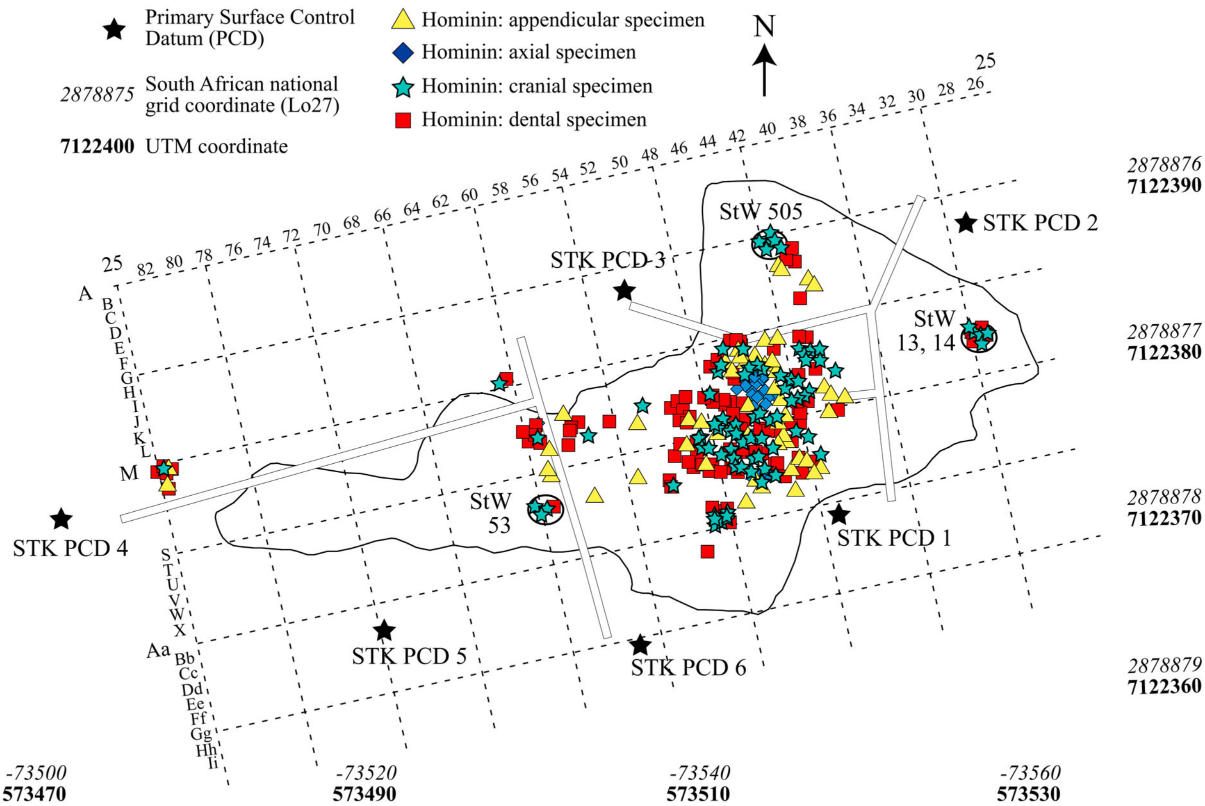

Figure 7 Plan view of the Sterkfontein surface excavation with Primary Control Datums (PCDs) and digitized excavation grid populated with 649 of the 'StW' prefixed hominins excavated between 1971 and 1993. The specimens are classified by significant body part (appendicular, axial, cranial and dental). A high resolution version of Figure 7 can be found in Online Supplement 5 (see http://dx.doi.org/10.1080/00934690.2016.1157679).

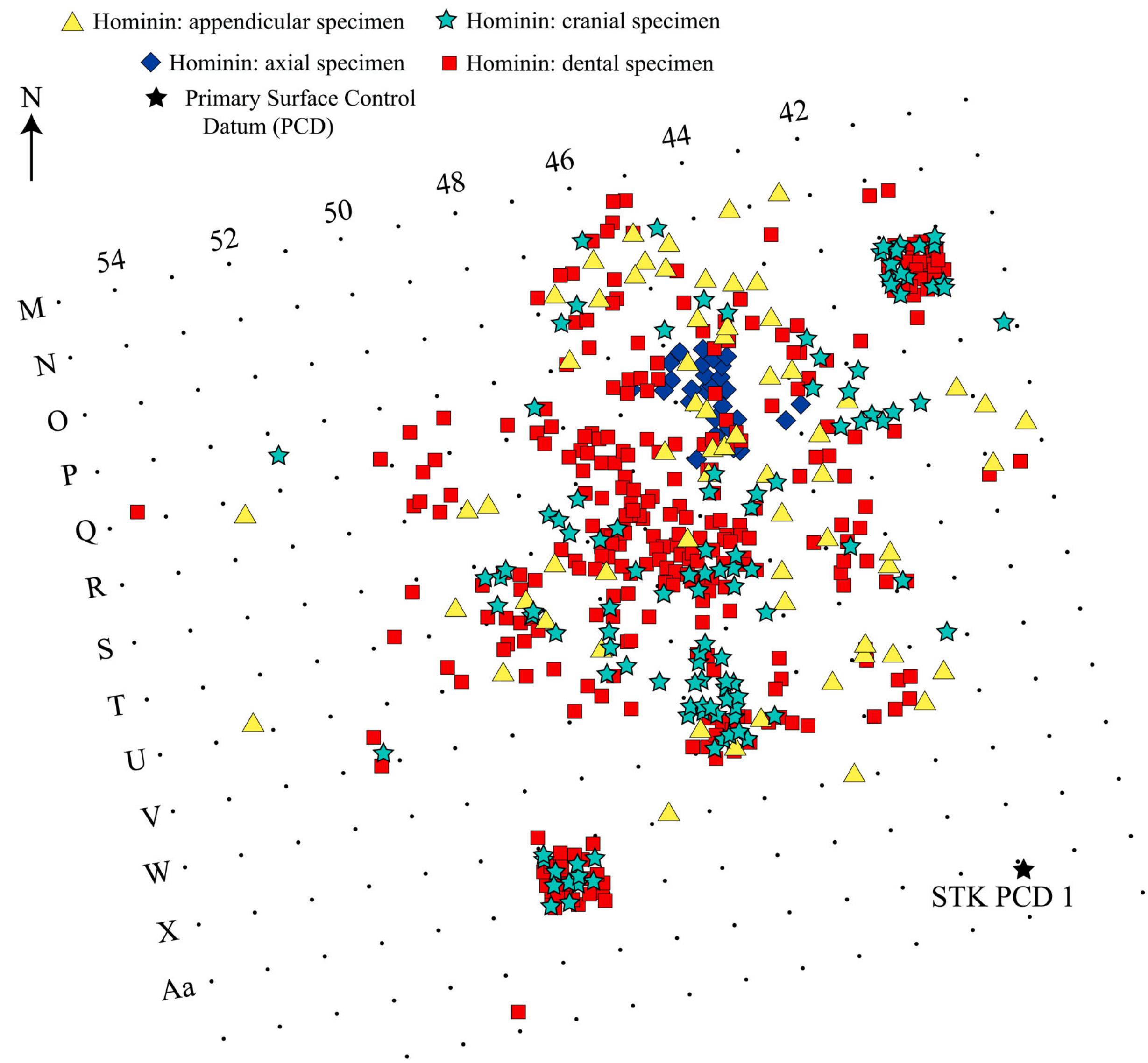

Figure 8 Expanded plan view of the concentration of 'StW' prefixed hominin fossils found between grid lines 39 to 52 and M through Aa (shown also in Figure 7).

function "Create Fishnet". The origin point is the northwest corner of Aa84 and the orientation point is the northwest corner of M84. Nevertheless, the National Grid Hartebeestoek 94 is still oriented to the North and therefore, when entering point data in the system, Westings (Y) will need to be entered as x values and Southings (X) as y values. The Sterkfontein grid was created based on an unmodified National Grid system (see defined Grid parameters in figure 4) by entering the Y value as longitude and X value as latitude. From the National Projected Coordinate System of South Africa Hartebeesthoek 94, Lo27 was chosen to define the points' projection. This projected dataset will display in ArcMap rotated 180°, i.e. pointing to the South rather than North. Nevertheless, being correctly projected it can now be re-projected and transformed into a global system such as WGS84 longitude and latitude.

Each grid square was assigned a unique identifier (the grid code) which serves as the link between the grid and any attributes that can be assigned to the grid square (i.e., geological type, excavation method, year of excavation, total number of fossils). The conversion to the metric system creates a slight cumulative error as one progresses from the point of origin to grid squares to its north and east. This error, which was verified against five surveyed points of the original grid, however, is small (maximum cumulative error in longitude and latitude was 0.060 m) and acceptable considering the resolution and accuracy of the original grid and fossil provenience data. The grid can be visualized against the newly surveyed features and other structures such as the walkways above the excavation (FIGS. 2, 4). It can also be re-projected and displayed against georeferenced satellite imagery at different resolutions. The grid enables us to use GIS display and analysis functions to express information on sediments, geological characteristics and faunal distributions recorded using the old grid system. As an example of this, Figures 7 and 8 present the distribution of 649 of the 'StW' prefixed hominin specimens excavated from Member 4 and Member 5 between 1971 and 1993. This assemblage is classified by significant body portion (axial, appendicular, cranial and dental). This relatively simple model is generated from data recorded in the Sterkfontein hominin catalogue which has been continually developed since 1966.

Even from this 2D representation, one can see that the axial elements are constrained to a limited area. These represent the vertebral column of StW 431, the partial *Australopithecus* skeleton discovered in 1987 (Tobias 1987; Toussaint *et al*. 2003). Axial elements are comparatively rare in the Sterkfontein hominin assemblage and provide useful taphonomic evidence suggesting the possible mode of accumulation and extent of localized post-depositional movement. The relatively intact nature of this specimen contrasts with the rest of the nearby hominin assemblage from Member 4 and may indicate a rare preservation of a death-trap accumulation. Modeling spatially associated non-hominin fossils may indicate whether other animals also fell to their deaths in a similar time period and were also preserved intact, or if StW 431 was a unique accumulation and exceptionally preserved. The distribution of this skeleton in relation to the deposit morphology and formation of Member 4 is particularly interesting given the rarity of partial skeletons. We can now model the distribution of individual elements of this specimen within the newly developed formation model of Member 4 to quantify depositional and post-depositional movement within this part of the deposit. A large amount of additional qualitative and quantitative data can be integrated into the database and visualized in the framework (e.g., specific skeletal element, element portion, specimen size and shape, individual age and fossil condition). Modeling the distribution of this evidence in conjunction with geological and stratigraphic information will enable us to more accurately reconstruct the formation history of the deposit and the interred assemblages.

Representation of hominin fossils in 3D

The Sterkfontein catalog of hominin fossils contains information on the location, skeletal element, fragment number, year of excavation and possible associations to other hominin specimens of over 750 fossils. Most studies on the spatial relationships of the Sterkfontein hominins have been conducted through analogue mapping, providing a horizontal or vertical perspective for visualization purposes only (e.g., Clarke 1985). Limited specimen attributes can be visualized on a single map and spatial statistical analysis is highly limited. Associations with other fossils or geological contextual information has never been specifically explored through a dynamic spatial framework at the site. The method used to record the location of the fossils during excavation (described above) provides a finite maximum resolution which allows us to attribute a fossil to a 3D spit in the grid system, but not to know where this fossil was located within that spit or square.

Conceptually, a single fossil should be, in a GIS, a single point, which represents a single entity with a single, unique spatial location. The problem is that single fossils recorded under the old spatial system do not have a unique provenience, but are identified by a common spit-unit provenience with a maximum resolution of $3 \times 3 \times 1$ ft. The logical way of portraying single fossils in 3D GIS is to create a single point in space to represent a hominin fossil within the boundaries of its recorded and modeled provenience spit. This gives us a resolution that is not higher than the spit resolution ($3 \times 3 \times 1$ ft), but allows us to visualize and study the hominin fossils singularly. The procedure for generating single points was carried out in ArcGIS 10.1 through the function "Create random points" which creates a set number of random points within a boundary (in this case the grid unit boundary). This function only operates within a two-dimensional framework, so it initially produced a 2D dataset. These random points were subsequently linked to the fossil database where each specimen is uniquely identified by an ID number and spatially characterized by a combination of row and column position (plus depth) in the reference grid. A unique code combining the ID and locational data was created, stored in a separate database field and used to link the fossils to the randomly created points in the horizontal grid system. In this manner single fossils can now be visualized and interrogated based on the characteristics collected in the database. Moreover, depth information can be used to visualize the fossils in three-dimensions using the application ArcScene. This simple operation allows the visualization of patterns in the data that would not have been possible outside a three-dimensional point cloud representation system.

Conclusions

The use of legacy fossil provenience data in modern GIS systems can be challenging, especially if older spatial systems utilized relatively low resolution data or spatial units were calibrated in different measurement systems. Both of these are the case at Sterkfontein. The situation is exacerbated by the complex stratigraphic relationships inherent in cave systems and which require high resolution stratigraphic analysis and the modeling of multiscale datasets. In order to reconcile the legacy fossil provenience data and new stratigraphic and geomorphological data, we first needed to establish a new, high resolution geospatial framework using South African survey conventions through the whole cave system. This enabled us for the first time to pinpoint, at a sub-cm resolution, the 3D positions of important specimens like StW 573 and StW 578 in relation to each other, the cave system, sedimentary and stratigraphic features, and the landscape (FIGS. 4, 5). We then surveyed and modeled Watts' 1967 imperially calibrated physical grid using a GIS framework. To populate our virtual grid, we modeled the location of the Member 4 *Australopithecus* fossils initially in 2D (FIGS. 7, 8). Modeling relatively high density but low resolution provenience data within a high resolution GIS framework provided challenges but was resolved through statistically random point creation and assignment within each square and spit. Although this allowed us to populate the old grid virtually, the original spatial resolution of the legacy dataset needs to be understood when conducting future spatial analysis of fossil distributions or associations with higher resolution stratigraphic data.

The next step is to extend the virtual grid vertically and populate it with not only hominin fossil data, but also artifact, faunal, floral, stratigraphic, sedimentological, geochemical and geomorphological spatial data in a true 3D framework. Every area of the Sterkfontein Caves will then be incorporated into a comprehensive 3D GIS framework, providing us a valuable analytical tool with which to interrogate legacy assemblage data and new multidisciplinary data yielded from excavations and specialist geological, sedimentological, faunal and archaeological investigations.

The potential benefits of such a system are extensive. The new framework will provide refreshed opportunities to spatially explore multiscalar/multidisciplinary datasets. In addition to statistical spatial analyses of traditional faunal investigations like taxonomic abundance and representation, we can model relationships between taphonomic data (bone surface modification features, bone breakage patterns, skeletal element representation and fossil condition) and high resolution sedimentological data (geochemical and micromorphology) and deposit geometry. We can now begin to model and represent complex stratigraphic/geomorphological data across the whole cave system during and after excavations through the integration of photogrammetric and remote sensing methods (LiDAR, IR, laser surface scanning, etc.). This includes modeling flowstone development, breccia contacts and lithological features within the hosting dolomites. Several of these techniques are being utilized in new excavations. Such a system is essential for clarifying the connections between dynamic landscape geomorphological and speleogenetic processes, depositional and post-depositional processes, and sedimentary facies and features. Incorporation of all of these factors is necessary for progressing our understanding of the context of the important fossil record preserved in the Sterkfontein Caves and building accurate and nuanced interpretations of hominin lifeways over the past three million years.

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References

Bamford, M. 1999. "Pliocene fossil woods from an early hominid cave deposit, Sterkfontein, South Africa," *South African Journal of Science* 95: 231–237.

Berceló, O. J. A., O. De Castro, D. Travet, and O. and Vicente. 2003. "A 3D model of an archaeological excavation," in M. Doerr and A. Sarris, eds., *The digital heritage of archaeology. CAA2002 Computer applications and quantitative methods in archaeology*. Crete: Archive of Monuments and Publications, Hellenic Ministry of Culture, 85–89.

Broom, R. 1936. "A new fossil anthropoid skull from South Africa," *Nature* 138: 486–488.

Broom, R., J. T. Robinson, and G. W. H. Schepers. 1950. "Sterkfontein Ape-Man Plesianthropus," *Memoires of the Transvaal Museum* 4: 1–117.

Bruxelles, L., R. J. Clarke, R. Maire, R. Ortega, and D. Stratford. 2014. "Stratigraphic analysis of the Sterkfontein StW 573 *Australopithecus* skeleton and implications for its age," *Journal of Human Evolution* 70: 36–48.

Clarke, R. J. 1985. "Early Acheulean with *Homo habilis* at Sterkfontein," in P. V. Tobias, ed., *Hominid Evolution: Past, Present and Future*. New York: Alan R. Liss Inc, 287–298.

Clarke, R. J. 1998. "First ever discovery of a well-preserved skull and associated skeleton of *Australopithecus*," *South African Journal of Science* 94: 460–463.

Clarke, R. J. 2013. "*Australopithecus* from Sterkfontein Caves, South Africa," in K. Reed, J. G. Fleagle and R. E. Leakey, eds., *The Paleobiology of Australopithecus*. Dordrecht: Springer, 105–123.

Eriksson, P. G., W. Altermann, O. Catuneanu, R. van der Merwe, and A. J. Bumby. 2001. "Major influences on the evolution of the 2.67–2.1 Ga Transvaal basin, Kaapvaal craton," *Sedimentary Geology* 141–142: 205–231.

Granger, D. E., R. J. Gibbon, K. Kuman, R. J. Clarke, L. Bruxelles, and M. W. Caffee. 2015. "New cosmogenic burial ages for Sterkfontein Member 2 *Australopithecus* and Member 5 Oldowan," *Nature* 522: 85–88.

Harris, T. H., and G. R. Lock. 1996. "Multi-dimensional GIS: exploratory approaches to spatial and temporal relationships within archaeological stratigraphy," *CAA95. Computer applications and quantitative methods in archaeology*. Analecta Praehistorica Leidensia, 28(II): 307–316.

Katsianis, M. 2004. "Stratigraphic modelling of multi-period sites using GIS: the case of Neolithic and Early Bronze Age Knossos," in K. Ausserer, W. Borner, M. Goriany and L. Karlhuber-Vockl, eds., *Enter the past. The e-way into the four dimensions of cultural heritage*. Oxford: Archaeopress, B.A.R International Series 1227, 304–307.

Kuman, K., and R. J. Clark. 2000. "Stratigraphy, Artefact Industries and Hominid associations, Member 5," *Journal of Human Evolution* 38: 827–847.

Kuman, K., and A. S. Field. 2009. "The Oldowan Industry from Sterkfontein Caves, South Africa," in K. Schick and N. Toth, eds., *The Cutting Edge: Approaches to the Earliest Stone Age*. Bloomington, Indiana: Stone Age Institute Press, 151–169.

Lieberwirth, U. 2009. *Landscape and archaeological deposits: 3D modelling and analysis of archaeological stratigraphy using Geographical Information Systems in archaeology—its possibilities and advantages.* Berlin: Lieberwirth Press.

Martini, J. E. J., P. E. Wilinger, H. F. G. Moen, and A. Keyser. 2003. "Contribution to the Speleology of Sterkfontein cave, Gauteng province, South Africa," *International Journal of Speleology* 32: 43–49.

Merlo, S. 2010. *Contextualising intra-site spatial analysis: The role of three-dimensional GIS modelling in understanding excavation data*. Unpublished Ph.D thesis, University of Cambridge.

Mitchell, A. 2011. "An introduction to coordinate systems in South Africa," http://www.durban.gov.za/City_Services/engineering%20unit/Surveying_Land_Information/Documents/An_introduction_to_Coordinate_systems_in_SouthAfrica.pdf

Mogg, A. O. D. 1975. *Important Plants of Sterkfontein, An Illustrated Guide*. Johannesburg: Bernard Price Institute, University of the Witwatersrand.

Nigro, J. D., W. F. Limp, K. K. Kvamme, D. J. De Ruiter, and L. R. Berger. 2002. "The creation and potential applications of 3-dimensional GIS for the early hominin site of Swartkrans, South Africa," in G. Burenhult and J. Arvidsonn, eds., *Archaeological informatics: pushing the envelope. CAA2001 Computer applications and quantitative methods in archaeology*. Oxford: Archeopress, B.A.R. International Series 1016, 113–124.

Nigro, J. D., P. S. Ungar, D. J. De Ruiter, and L. R. Berger. 2003. "Developing a Geographic Information System (GIS) for mapping and analysing fossil deposits at Swartkrans, Gauteng Province, South Africa," *Journal of Archaeological Science* 30(3): 317–324.

Parker, A. 2011. "The South African Coordinate Reference System (Part1)," *Position IT* , Nov/Dec, 22–25.

Parker, A. 2012. "The South African Coordinate Reference System (Part2)," *Position IT*, Jan/Feb, 26–30.

Partridge, T. C., and I. B. Watt. 1991. "The stratigraphy of the Sterkfontein hominid deposit and its relationship to the underground cave system," *Palaeontologia Africana* 28: 35–40.

Partridge, T. C., D. E. Granger, M. W. Caffee, and R. J. Clarke. 2003. "Lower Pliocene hominid remains from Sterkfontein," *Science* 300: 607–612.

Pickering, R., and J. D. Kramers. 2010. "Re-appraisal of the stratigraphy and determination of new U-Pb dates for the Sterkfontein hominin site, South Africa," *Journal of Human Evolution* 59: 70–86.

Reynolds, S. C., and J. M. Kibii. 2011. "Sterkfontein at 75: review of the palaeoenvironments, fauna and archaeology from the hominin site of Sterkfontein (Gauteng Province, South Africa)," *Palaeontologia africana* 46: 59–88.

Stratford, D. J., L. Bruxelles, R. J. Clarke, and K. Kuman. 2012. "New stratigraphic interpretations of the fossil and artefact-bearing deposits of the Name Chamber, Sterkfontein," *South African Archaeological Bulletin* 67: 159–167.

Stratford, D. J., S. Grab, and T. R. Pickering. 2014. "The stratigraphy and formation history of fossil- and artefact-bearing sediments in the Milner Hall of Sterkfontein Cave, South Africa: New interpretations and implications for palaeoanthropology and archaeology," *Journal of African Earth Sciences* 96: 155–167.

Stratford, D. J., J. L. Heaton, T. R. Pickering, M. V. Caruana, and K. Shadrach. 2016. "First hominin fossils from the Milner Hall," *Journal of Human Evolution* 91: 167–173.

Tobias, P. V., and A. R. Hughes. 1969. "The New Witwatersrand University Excavation at Sterkfontein: Progress Report, Some Problems and First Results," *South African Archaeological Bulletin* 24: 158–169.

Tobias, P. V. 1987. "21st Annual Report of PARU and its Precursors," Department of Anatomy, University of the Witwatersrand, Johanneburg.

Toussaint, M., G. A. Macho, P. V. Tobias, T. C. Partridge, and A. R. Hughes. 2003. "The third partial skeleton of a late Pliocene hominin (StW 431) from Sterkfontein, South Africa," *South African Journal of Science* 99: 215–223.

Wilkinson, M. J. 1973. *Sterkfontein cave system: evolution of a karst form*. M.A. thesis, University of the Witwatersrand.

Wilkinson, M. J. 1983. "Geomorphic perspectives on the Sterkfontein *Australopithecine* breccias," *Journal of Archaeological Science* 10: 515–529.