

The Creation and Potential Applications of a 3-Dimensional GIS for the Early Hominin Site of Swartkrans, South Africa

Joseph D. Nigro

Center for Advanced Spatial Technologies /
Department of Anthropology
University of Arkansas
Ozark Hall, Room 12
Fayetteville, AR 72701, USA

Phone: +1-501-582-0790 - Fax: +1-501-575-5218 - E-mail: jnigro@cast.uark.edu

W. Fredrick Limp

Center for Advanced Spatial Technologies /
Department of Anthropology
University of Arkansas
Ozark Hall, Room 12
Fayetteville, AR 72701, USA

Phone: +1-501-575-7909 - Fax: +1-501-575-5218 - E-mail: fred@cast.uark.edu

Kenneth K. Kvamme

Department of Anthropology
University of Arkansas
Old Main 330
Fayetteville, AR 72701, USA

Phone: +1-501-575-4130 - Fax: +1-501-575-6595 - E-mail: kvamme@mail.uark.edu

Darryl J. de Ruiter

Palaeoanthropology Unit for Research and Exploration
Department of Palaeontology
Bernard Price Institute for Palaeontology
Private Bag 3
University of the Witwatersrand
2050 Johannesburg, South Africa

Phone: +27-11-717-6668 - Fax: +27-11-339-7202 - E-mail: deruidt@science.pg.wits.ac.za

Lee R. Berger

Palaeoanthropology Unit for Research and Exploration
Department of Palaeontology
Bernard Price Institute for Palaeontology
Private Bag 3
University of the Witwatersrand
2050 Johannesburg, South Africa

Phone: +27-11-717-6668 - Fax: +27-11-339-7202 - E-mail: 106lrb@cosmos.wits.ac.za

Abstract: The accumulation of fossil remains, bone tools, and stone tools at the site of Swartkrans has been attributed to a variety of agents including hominin activity, carnivore activity, alluvial deposition, and gravitation. In fact, the accumulations discovered at Swartkrans and other Plio-Pleistocene cave sites in South Africa have probably resulted from a combination of these factors. In order to explore further the taphonomic nature of this deposit a Geographic Information System (GIS) was constructed incorporating all of the existing information produced from the Swartkrans excavations and a recent survey of the site. The final product represents a digital archive of Swartkrans data that allows the user to simultaneously visualize and analyze fossil, artifact, and geological data together within their spatial contexts allowing a more comprehensive investigation of the site post-excavation. The mapping and 3D reconstruction of sites such as Swartkrans present challenges when using traditional GIS approaches. These issues are addressed, as well as the potential applications of the system.

Key words: Geographic Information Systems, GIS, palaeoanthropology, hominin, hominid, taphonomy, fossil assemblages, intrasite analysis, Plio-Pleistocene caves, Swartkrans

Introduction

Travertine caves in the Sterkfontein Valley of South Africa's Gauteng province have yielded a rich array of Plio-Pleistocene faunal material. The site of Swartkrans, for example, has produced the single largest sample of fossils attributable to the genus *Paranthropus* in addition to numerous fossils belonging to the genus *Homo* as well as a variety of bone and stone tools. To date, approximately 350,000 pieces of fossil bone representative of both human and non-human species (Brain 1993:3), along with almost 900 stone tools and 70 bone tools, have been discovered at this site (Brain/Shipman 1993:214).

The decisive work of C.K. Brain, conducted between 1965 and 1986, has provided many important clues concerning the accumulation of the fauna at Swartkrans. Based on carnivore markings on the bones, as well as geological formation processes, Brain suggests that the fossil accumulations of Swartkrans might be best attributed to carnivore activity (Brain 1968, 1969, 1970, 1974, 1981, 1993). Recent studies have yielded an array of possible hominid-derived tools and have, by implication, raised questions concerning the formation processes responsible for their deposition (Clark 1993; Brain/Shipman 1993; Backwell/d'Errico 2001) drawn from the spatial relations of the remains at the site. In order to test the hypothesis that a variety of agents were responsible for the accumulations at Swartkrans and to extract and isolate these complex agents of accumulation, a Geographic Information System (GIS) was constructed.

In 1999 the Palaeoanthropology Unit for Research and Exploration at the University of the Witwatersrand in conjunction with the University of Arkansas' department of Anthropology and its Center for Advanced Spatial Technologies assigned the first author to the task of developing a GIS for Swartkrans. The project arose as an exercise in applying recent technological developments to a site that was excavated at a time when GIS was either in its infancy in regards to archaeological applications or not an option at all. Swartkrans was used as the pilot site to demonstrate how this technology is capable of deriving new or enhanced information from existing data and facilitating current methods of analyses. It was chosen because of its relatively small size due and the existence of meticulously recorded fossil, artifact, and geological data collected during C.K. Brain's excavations.

The specific goals of the project were: 1) to create a system that can assist in further understanding the stratigraphy present at Swartkrans and other cave sites; 2) to create a system that can be used to further explore the relationships between the fossil and artifact distributions of these sites; 3) to realize the implications and constraints of the technology involved in creating such a system; 4) to construct a 3D model of Swartkrans in order to improve the grid-based provenience information of the finds recorded previously; and 5) to reconstruct C.K. Brain's excavation. The Swartkrans GIS was demonstrated to be very beneficial in addressing all of the goals listed above and has resulted in the creation of a digital archive encompassing all available site information. This accomplishment will allow researchers to virtually re-excavate the site an infinite number of times, a task that would otherwise prove impossible.

Provenience data of the fossils and artifacts

Palaeoanthropological exploration commenced at Swartkrans in 1948, but it wasn't until 1979 when systematic excavations were first conducted at the site. Many important specimens came to light during the first three decades of work there, including the well-known cranium of an adult *Paranthropus robustus* (SK 48). Unfortunately, all these early discoveries are lacking the vital provenience information needed to accurately reposition them in three-dimensional space (Brain 1981: 221). This is an important fact because it hinders us from producing a total reconstruction of the geological and fossil content of Swartkrans.

In 1979, this problem was remedied with the establishment of a datum, in the form of a permanent metal grid, over the Outer Cave area (fig.1). Although the main bars of the grid were constructed of rigid metal, the smaller units were made of wire and spaced every meter. Over areas representing Members (strata) 1 and 2 each grid square was divided into 50 cm² quadrants while subdivided even further into 25 cm² sub-quadrants over Member 3 due to the density of burnt bone found in twenty consecutive spits throughout a 6-m vertical profile (Brain 1993: 4). The excavation was mainly carried out in 10-cm spits in all areas of the Outer Cave, but extending as deep as 1m in certain places.

Mapping the existing site

The first stage of the project involved mapping Swartkrans as it exists today. C.K. Brain was asked to visit the site to assess if there had been any major shifts in the positions of the remaining geological structures since his first removal of excavated material, material that may have supported these structures previously. Fortunately, no major changes had taken place and so the site as it exists today reflects the site upon initial excavation in 1979 minus the excavated matrix (Brain 1999). This was useful information since the purpose of the survey was to incorporate all of the existing geology of the site into the GIS in an attempt to increase the recorded provenience of the known fossils and artifacts. For example, if a fossil was recorded to have come from the NW quadrant of the grid-based position E4S7, the accuracy of the provenience would be 50 cm² x 10 cm. By mapping existing structures, the accuracy of the provenience information could be increased if unexcavated material still remains in E4S7 thus decreasing the volume where the fossil was originally found to less than 50 cm² x 10 cm (fig.2). These structures were sometimes recorded in the excavation notes, but mapping the site filled the data gaps where representative diagrams are non-existent. In addition to increasing the provenience data of the finds, the mapping of Swartkrans provides both a three-dimensional matrix into which the excavated data can be repositioned and a complimentary source of geological information derived from the attributed survey points.

The survey was carried out using a Wild T1010™ theodolite with a Leica Distomat™ Laser electronic distance meter attachment (fig.3). A total of 14,885 survey points were collected representing the Inner, Outer, and Lower cave systems.

The Outer Cave, now a sinkhole due to collapsed dolomite roof blocks, was the only area recorded with the intention of creating a 3D reconstruction, given available provenience information. The base perimeters of the Inner and Lower caves, however, were recorded to determine their spatial orientations within the cave network.

The survey was based on C.K. Brain's grid system to facilitate the incorporation of the data derived from his excavation notes within the 3D model. As a result, the origin (represented by the center of the grid structure) and the north line (the metal bar leading from the origin to the "Hanging Remnant", a landmark feature) remained the same as those used during the excavations (fig.4). One obstacle encountered at this point was the problem of dealing with the wire section of the grid where the wires were either sagging or gone completely. This made it impossible to map these grid sections and, as a result, each digitized excavation diagram was unable to be reprojected individually to its original location. Fortunately, the metal bars constructing the main axes of the grid were still in place and so all of the excavated squares were reprojected as one unit based on these axes.

Fifty-nine control points were set up around and within the site from where each feature was recorded (fig.5). These points were established by resecting off of two known points beginning with the origin point and the point marking the contact area where the north line touches the Hanging Remnant. Side shots were collected every 10 cm vertically while the horizontal mapping resolution ranged from between 25-50 cm depending on the degree of topographical variation of the feature. For example, a wall of breccia with small inclusions is relatively uniform so fewer points were taken to represent it, while a dolomite roof block is characterized by undulations and crevices and was respectively assigned more points due to its complexity (fig.6). These mapping intervals were chosen to be consistent with Brain's excavation levels. A line level was used as a rough guide for mapping. For areas that were inaccessible, the vertical and horizontal measurements of the theodolite were monitored and points remained unrecorded until these readings were consistent with the appropriate intervals. This degree of accuracy was sufficient enough to allow a detailed image of the terrain to be produced from the interpolation of the survey points. Attributes for the points were recorded, including feature descriptions, geological material, sediment color, degree of calcification, cave area, Member (strata), and the cardinal direction that the feature is facing. This last attribute was essential for the interpolation of the data using Voxel Analyst, our principal software, for reasons discussed below.

The survey data were stored on a memory card that was transferred daily from the total station to a Wild GIF 10 data collector. The data were then downloaded from the data collector to a Dell Inspiron 3200 laptop using a data transfer program called Convtran. The point IDs, X- coordinates, Y-coordinates, and Z-coordinates were saved in text file format. Finally, these space-delimited files were imported into MS Excel where field headings were assigned and attributes were entered manually. The application of photogrammetry was not considered for this project due to the lack of proper equipment and training and to the site being characterized by small recesses that are easier to

record with a laser than with a camera. In addition, a method that can be used in dark, subterranean networks needed to be devised in order to extend this work to other cave sites.

Constructing the Inner and Lower Cave base perimeters and the excavation grid

The survey points representing the base perimeters of the Inner and Lower caves, as well as Brain's excavation grid, were imported into AutoCAD MAP R3. Each consecutive point was connected by a line using the 3D-polyline command, thus producing a three-dimensional vector representation of each feature. Upon completion these layers were saved as data interchange files (.dxf) and imported into ArcView 3.2 using the CAD Reader extension. It was essential that these layers were saved in .dxf format, as opposed to saving them as AutoCAD drawing files (.dwg) or exporting them as ArcView shapefiles (.shp) or Microstation design files (.dgn). The reason for this is that .dxf is the only format that maintains the 3D spatial relationship created by connecting two points at varying elevations when exporting them from AutoCAD MAP R3 into ArcView 3D Analyst.

Interpolation of 3D data and the limitations of conventional GIS data models

A range of GIS and related software packages, including Surfer 7, ArcView 3.2, Idrisi 3.2, Slicer-Dicer and GRASS 4.0 were tested to see how their interpolation algorithms would handle point data that had multiple z values for the same x,y coordinate pair, representing the natural geological overhangs at Swartkrans (fig.7). After many attempts, it was realized that none of the interpolation methods were suitable for processing this type of data. Due to the data structures of these software packages, the resulting interpolated image contained severe errors making the 3D reconstruction of Swartkrans highly inaccurate in certain areas. Some of these software packages, such as Surfer 7, prompted the user to choose a calculation parameter, such as minimum, maximum, or average, for points possessing multiple z values. Other software packages, such as ArcView 3.2, failed to grant the user the option to select the points containing duplicate x, y coordinate values that were to be included in the interpolation. In both cases the resultant output was characterized by data spikes in places where overhangs are present at the site, such as below the Hanging Remnant (fig.8).

This is not surprising because the data model of a conventional GIS is structured in two dimensions where features are assigned x and y spatial coordinates with an attribute defining some aspect of the feature, such as soil type. Two-dimensional mapping results in planar surfaces where each data layer represents some characteristic found on a single surface. When the attribute signifies an elevation or a measured value of some sort then the data model is considered to be surficial, or representing 2.5D data. Surficial data can be visualized in three dimensions although it lacks 3D topology. A classic example of this is a Digital Elevation Model where height is considered an attribute (Raper 1989; Turner 1989). Unfortunately, up to this point archaeological applications have been limited by the constraints

of these two types of data models. Yet, excavated material exists on multiple artificial surfaces overlaying one another in 3D space, making these data models insufficient. As a result, spatial modeling software was used instead of traditional GIS algorithms to produce an interpolated image containing all overhanging features. For an extensive overview and discussion concerning the progressive stages and limitations of representing multidimensional data in archaeology, refer to Harris and Lock (1996).

Constructing the 3D Model of the Outer Cave

Voxel Analyst, developed by the Intergraph Corporation, provided the solution to the problem mentioned above since it recognizes three independent axes (x,y,z). The software played a crucial role in this project and was responsible for making the 3D reconstruction of Swartkrans possible. Voxel Analyst is a data visualization and analysis tool that is designed to characterize subsurface data and to enhance the understanding of multi-dimensional data relationships within a 3D volumetric data set. A voxel, or volumetric element, is a three-dimensional version of a pixel, depicted as a cube. The voxel data model was introduced in commercial software that was developed for the purpose of oil and gas exploration. It is currently used for a wide variety of applications, from reservoir engineering to mining exploration (Harris/Lock 1996; Turner 1989). Utilizing this type of software resulted in an innovative way to accurately interpolate a terrain model of an archaeological site in true 3D space.

In order to model the existing terrain at Swartkrans using Voxel Analyst, the site had to be viewed as a solid block. Thus, the solid earth as well as the void areas representing air that once contained the excavated material had to be assigned unique numeric values respectively. This allowed the software to acknowledge both features as two distinct phenomena interlocked in three-dimensional space (fig.9a). Since a reflector card was not used to collect survey points in mid-air with the laser during the initial survey, the air component was assigned using another method. Essentially all of the survey points representing the cave surface were duplicated in MS Excel and repositioned 1 cm (the distance between the center of two adjacent voxels) away from the surface in the appropriate cardinal direction in order to create the outer boundary of the air mass (fig.9b). This made it possible for the software to identify the interface between the cave structure and the air and to create a thin surface located where each voxel adjoined each other (fig.9c). This procedure eliminates the problem of spatial inexactitude that is usually inherent in voxel-based systems due to the voxel size and the lack of precise boundaries between spatial entities (Jones 1989).

Man-made features at the site, such as steps, were initially mapped and then eliminated from the survey data prior to interpolation of the natural surface. The text file representing all the survey points was brought into a text editor. A carriage return, necessary for the software to recognize the file, was placed after the last line of the data. The file was saved in .smp format and imported into Voxel Analyst. The 14,489 (14,885 minus the man-made features) points were interpolated using the

Shephard's Method algorithm, an inverse-weighted approximation. This was the most appropriate interpolator since it is ideal for rough and unevenly distributed data and it satisfies the Maximum Principle in which interpolated output values will not exceed the range of the original input values (Intergraph 1994). The output represented an accurate reconstruction of Swartkrans, including all existing overhangs. The final model was exported from Voxel Analyst as a .dgn file, opened using the CAD Reader extension in ArcView 3.2, and finally converted to a .shp file.

A mistake realized in hindsight, after the survey was completed, is that no survey points were recorded on the ground level of the site since there isn't much variation in elevation. This resulted in the appearance of a "bulbous floor" in the final reconstruction of the site due to the scarcity of points representing these areas (fig.10). The ground level, fortunately, represents areas that may be excavated and recorded at a later date and so the data can always be incorporated into the GIS in the future.

Converting the excavation notes into digital format

Brain's excavations lasted from 1979-1986 and produced several volumes of excavation notes outlining in meticulous detail the geological contents, and, in some instances, the fossil content of each excavated grid square. Converting information contained in these notebooks into digital form was essential to rebuild the site as it existed prior to Brain's excavations. By doing this, the user of this system will be able to view specimens within their associated strata once again and to conduct a virtual re-excavation of the site.

The excavation diagrams were digitized using a Microscribe Digitizer, though any digitizing would have sufficed (fig.11a). Initial calibration was performed using Inscribe software to define the origin, coordinate axes and scale. Most of the diagrams were drawn on a standard form where each side of the grid-square represented exactly 80 mm (fig.11b). All of the diagrams were rescaled to convert their original dimensions to equal 1m². Sketched drawings were also included to provide information where standard diagrams were unavailable (fig.11c). Although these drawings are less accurate representations, it is better to have some information present in the GIS for these areas than not to have any at all. Each diagram was digitized, reprojected to its appropriate grid square in true geographic space, and stored on a unique elevation layer in AutoCAD MAP R3. The elevation layer of the diagram was assigned based on the bottom-most level of the 10-cm spit from which it was drawn. For instance, if a grid square was excavated at 80 - 90 cm below the datum, then the data in that area were assigned an elevation of -0.900 m due to the fact that each diagram was drawn after the material was removed from the grid square. Each elevation layer with associated excavation data was exported as an ArcINFO coverage and brought into PC ArcINFO to create topology. The attributes were then extracted from the excavation notes and entered in MS Excel to compile a table¹ of geological features. The digitized diagrams were finally imported into ArcView 3.2 where the attributes were linked to the appropriate feature using unique ID values selected as the join field or

primary key (fig.12). These polygon themes were then clipped based on the appropriate elevation layers extracted from the 3D model. This procedure combined the new data with the old and ensured that the existing geological information of the site was taken into account before the finds were inputted into the system. At times, entities derived from the excavation note descriptions, as opposed to the diagrams or sketches, were deleted as a result of the clipping process. These features were reconstructed later using ArcView editing functions.

Creation of the fossil and artifact database

Throughout the 1999 project year, one of the authors (DJD) compiled a database of the fossils and artifacts found at Swartkrans. This task was carried out at the Transvaal Museum in Pretoria, South Africa, where all relevant information previously gathered was entered on computer using MS Access. The finds entered were only those from Members 1, 2, and 3 that were assigned accession numbers beginning with SKX. The resulting database contains almost 22,000 records with attributes recorded for numerous fields². The fields created for the survey and excavation data were kept consistent with those listed above, when applicable.

Point representation of the fossils and artifacts in three-dimensions

Although the locations of many of the finds were recorded only to the grid system and spit (level), it seemed more beneficial to represent them as individual points within the GIS. A point theme allows the user to visualize the fossils and artifacts of interest in and about the general area of their discovery and to identify clusters of certain fossils more readily without having to deal with the confusion of having each grid square representing multiple points at a time.

Random numbers were used to place the points within the assigned grid squares by combining functions from ArcView 3.2 and SPLUS 2000, a statistical software package. To create a series of random points in specific areas of the excavation grid, a random point generator (randpts.avx)³, downloaded from the ESRI web page⁴, was employed. The extension allows the user to specify the number of random points to be created, as well as the region of interest within which the point generation will be limited. This second parameter acts as a mask. Since this extension is limited to producing points in x, y coordinate space only, this procedure was carried out on one excavation square at a time, combining all of the associated points regardless of elevation. For example, if 500 artifacts were assigned to have come from all spits in E3S2, then 500 random points were generated within this area. Since the extension is incapable of generating points with z values, SPLUS was used for this task. The number of points found in each spit, excavated in the same grid square location, was counted and the random point generator in SPLUS was used to derive random z values to represent them. These values were then added to the table containing the x, y coordinates and selected to transform the point theme into a 3D shapefile. The fossil/artifact database was then linked to these points using unique ID numbers as the join field.

The amalgamation of the data within ArcView 3D Analyst

Once these three sources of Swartkrans data were either created or converted into a usable digital format they were displayed together using the 3D Analyst extension for ArcView. All of the data was spatially sound and overlaid each other perfectly (fig.13). Now that these themes were brought into 3D Analyst, the three-dimensional capabilities of the software needed to be assessed.

Although 3D Analyst would be expected to have three-dimensional analytical capabilities based on the name, the data model of the software remains surficial. The Swartkrans data can be displayed very nicely within the module, but proper 3D analyses and functionality, such as nearest neighbor and buffering operations, cannot be conducted due to the lack of 3D topology. For example, when the user wanted to know how many fossils lie within 10 cm of a dolomite block, 3D Analyst would only output the points that are within a 10 cm area of dolomite on the same horizontal plane not taking into account the points that lie above, below, or at angles from the block. This is a serious problem since it limits the integration of these datasets to visual analysis, besides the conventional 2D and 2.5D operations.

3D buffering operation and potential applications

In an attempt to bypass this obstacle, an Avenue script was created that is successful in creating three-dimensional buffer zones. The script, however, is limited to the buffering of point features. An Avenue script (sphere3D_creator)⁵ that can create a spherical graphic around a user-specified point, at a defined radius, was downloaded from the ESRI web page⁶. The script was combined with another developed independently that uses a 3D Euclidean distance calculation in order to measure the distance from a user-defined point to all other points in the dataset. The calculation is as follows: $\text{SQRT}(\left(\left(\left(x\text{coordinate of specified point} - x\text{ coordinates of all points}\right)^2\right) + \left(\left(y\text{coordinate of specified point} - y\text{ coordinates of all points}\right)^2\right) + \left(\left(z\text{coordinate of specified point} - z\text{ coordinates of all points}\right)^2\right)\right)) \leq \text{specified range represented by the radius of the spherical buffer}$.

The spherical graphic was included solely as a visual aid to highlight the area of interest in three-dimensional space. The degree of transparency of the sphere can be regulated allowing the user to view the points floating within it (fig.14).

Besides using 3D buffering to examine taphonomic relationships of specified skeletal remains and artifact distributions based on a number of attributes, it can be used in identifying potential specimens for bone refitting. The user can define a distance in all directions from one fossil to extract specific fossil types that are located within this distance. For example, all bovid class III metapodials can be identified within 1-m of a given specimen to see if there are any other specimens possibly representing the same individual in that area. This feature is also useful when attempting to determine whether or not a clustering of fossils represents an individual animal within the fossil deposit.

Another potential query, presently untested, would involve the conversions of all polygonal data representing the geology of the site into point data, since the 3D buffer script only works on point themes. This may enable the user to actually perform distance operations to seek associations between the fossils/artifacts and the geology in the way described above, but instead taking into account points with geological attributes. This may allow the user to overcome the obstacle stated above and discover what fossils do lie within 10 cm of a dolomite block.

Artifact and fossil distributions

It is widely accepted by researchers that the patterned spatial distributions of specimens found in these cave sites may reflect the behavior of various species while an unpatterned or scattered distribution may imply deposition by natural phenomena or episodic deposition by a variety of animals. Dolomitic caves, depending on size and location, function as lairs, shelters, or feeding places. In order to understand fossil assemblages in these caves, fossil distribution patterns must be recognized as unique indicators of animal behavior (de Ruiter/Berger 2000: 665-666) For example, hyaena dens usually consist of highly fragmented bone and scattered carcass elements (Brain 1981), while felid activity within caves often results in the presence of numerous articulated skeletons. Due to the complex nature of these cave sites, other factors such as local environmental conditions and the associated animal community need to be taken into account in order to achieve a more complete understanding of these distributions (de Ruiter/Berger 2000: 682, 684). A GIS is capable of handling complex data of these types. The GIS is ideal for the examination of artifact and fossil distributions for many reasons. The ability to view and rotate a combination of elements in 3D space is the most obvious (fig.15). The query builder in ArcView can be used to extract a sample of elements restricted to a large number of associated attributes on the fly, such as the distal limb sections of all species possessing chew marks (fig.16). Informative statistics related to the fossil population and important for understanding faunal accumulations in cave assemblages (de Ruiter/Berger 2000: 683), such as Minimum Numbers of Individuals (MNI) or Minimum Numbers of Elements (MNE), can also be calculated quickly from the data. Using this system is more efficient than manually plotting or attempting to understand spatial relations of entities characterized by numerous variables based solely on the textual information recorded previously. These finds can once again be studied within their original geological context, possibly providing further insight into environmental conditions and processes responsible for the accumulations. Another benefit of archiving these data using ArcView is that statistical analyses can be performed conveniently using the SPLUS extension.

Mapping fossil and artifact densities

Density maps are useful for looking at patterns in the data by identifying high and low concentrations of specified elements (Mitchell 1999). Although this function is limited to 2D space in ArcView, it can still be useful in detecting clusters that are indicative of a vertical filtration of fossils and artifacts into the

cave (fig.17). This is important because the difference in the horizontal and vertical distributions of the finds can reveal whether or not the cave represents a living floor or if the finds just fell into the cave through an opening in the surface (Clark 1993: 167).

Geological applications

Voxel Analyst can be used to further explore the interrelations of the site's geological components, such as specified pockets of material, that have been encompassed by the deposition of younger strata, and to further study the complex processes responsible for cave formation. The slicing and dicing capabilities of the software allow the user to define the yaw, pitch, and distance of a plane in order to extract strata interfaces, profiles, sections, and iso-surface values (fig.18). The excavation diagrams may also be imported into Voxel Analyst where each spit can be interpolated vertically as long as continuous numeric values are assigned to each category of geological material. Essentially, it would appear as if the user is virtually back-filling the site by converting the planimetric data to volumetric data representing geological solids. Voxel Analyst is also capable of measuring volumes and surface areas and so the amount of excavated material can easily be calculated if necessary.

Geological features, such as waterworn pebbles, can also be queried and displayed using 3D Analyst (fig.19). In this example, the output may allow one to detect paths or clusters of this material transported by water into the cave (Brain 1958). A query like this may reveal more information concerning the previous locations of cave openings that allowed transport of material to lower levels.

Summary

Attempts to easily explore and understand complex relationships between archaeological phenomena and associated strata in three-dimensional space has been hindered for more than a century, but solutions are slowly being advanced through the use of computer technology. Currently the capability to record these phenomena in 3D exists but the analysis tools essential for their interpretation do not. Multidimensional GIS would allow nearest-neighbor functions to be performed, as well as, allow the user to devise 'what if' scenarios (Harris/Lock 1996: 309). At present a GIS package that possesses a truly functional 3D data model has not been developed, limiting the archaeologist to analyze data within a vertical stack of planimetric surfaces. This was a limitation encountered at Swartkrans because the excavation material was recorded as a series of two-dimensional surfaces that had to be translated to conform to 3D space. This problem may be overcome if future excavations are recorded using the methodology described for creating the 3D model of Swartkrans.

Due to these limitations, most GIS and surface analysis applications have been carried out on a regional scale while few have been conducted at the intra-site level (Harris/Lock 1996: 307). Although these factors introduced many obstacles

throughout the course of this project, the Swartkrans GIS is another step towards three-dimensional intra-site investigations of archaeological sites. The system developed is important for archiving and visualizing fossil, artifact, and geological data within their spatial contexts and providing a small set of tools for analyzing the interrelations of these 3D datasets. It still remains to be seen whether or not such a system can provide new information on the processes responsible for the accumulations found at Swartkrans and other cave sites. The answer will not be known until all data entry is complete and actual taphonomic investigations begin.

Acknowledgements

The authors would like to thank: the Palaeo-anthropology Scientific Trust for funding the project, ESRI, AutoDesk, and the Intergraph Corporation for software access and technical support, Peter Ungar, C.K. Brain, P.V. Tobias, Ron Wright, John Wilson for assistance in Avenue scripting, John Duncan for help with mathematical formulas, Brian Norris, Lewis Bowker, and Colin Menter for development of the survey design, Sohayla Hamon for the drive and inspiration needed to complete the project, Deano Stynder, Lloyd Rossouw, Alynne Bayard, Brian Culpepper, Jim Schryver, Jose Aguayo, Bruce Gorham, Terri Gorham, and the folks who reside in CAST 209 and 214.

End notes

¹ The table consisted of the following fields: ·Square, ·Level, ·Date of Excavation, ·Quadrant, ·Sub-quadrant, Member, ·Geological Material, ·Sediment Color, ·Degree of Calcification, ·Degree of Hardness, ·Presence/Absence of Granular Particles, ·Number of Stones, ·Presence/Absence of Manganese Dioxide, ·Number of Rocks, ·Presence/Absence of Decomposed Dolomite, ·Presence/Absence of Ash-like Material, ·Elevation, ·Depth of Spit, and ·Other Notes.

² The fields consisted of: ·Member, ·Square, ·Level, ·Quadrant, ·Sub-quadrant, ·Date, ·Order, ·Family, ·Tribe, ·Genus, ·Species, ·Body Weight Class, ·Alcelaphine/Bird Size, ·Carnivore Size, ·Element, ·Number Bone Flakes/Pebbles, ·Potential Tool, ·Burnt Categories, ·Upper/Lower Right Incisor1 (RI1), ·RI2, ·RI3, ·RI4 ·Right Canine (RC), ·Right Premolar1 (RP1), ·RP2, ·RP3, ·RP4, ·RM1, ·RM2, ·RM3, ·Left Incisor1 (LI1), ·LI2, ·LI3, ·LI4, ·Left Canine (LC), ·Left Premolar1 (LP1), ·LP2, ·LP3, ·LP4, ·Left Molar1 (LM1), ·LM2, ·LM3, ·Right Deciduous Incisor1 (Rdi1), ·Rdi2, ·Rdi3, ·Right Deciduous Canine (Rdc), ·Right Deciduous Premolar1 (Rdp1), ·Rdp2, ·Rdp3, ·Rdp4, ·Right Deciduous Molar1 (Rdm1), ·Rdm2, ·Left Deciduous Incisor1 (Rdi1), ·Rdi2, ·Rdi3, ·Right Deciduous Canine (Rdc), ·Left Deciduous Premolar1 (Ldp1), ·Ldp2, ·Ldp3, ·Ldp4, ·Left Deciduous Molar1 (Ldm1), ·Ldm2, ·Indeterminate Incisor, ·Indeterminate Canine, ·Indeterminate Premolar, ·Indeterminate Molar, ·Indeterminate Tooth, ·Teeth Portion, ·Extent of Wear, ·Diagnostic Feature 1, ·Diagnostic Feature 2, ·Diagnostic Feature 3, ·Diagnostic Feature 4, ·Diagnostic Feature 5, ·Side, ·Degree of Completeness, ·Bone Portion (Marean), ·Shaft Fragment (Villa & Mahieu), ·Specimen Physically Examined, ·Age, ·Sex, ·Surface Damage, ·Surface Damage 2, ·Surface Damage 3, ·Fracture Pattern, ·Fracture Angle, ·Fracture Outline, ·Weathering Stage, ·Shaft

Circumference, ·Tooth MD Length, ·Tooth BL Width, ·Tooth Crown Height, ·Bone Maximum Length, ·Bone Maximum Width, and ·Comments.

³ This extension was created on February 13, 2001 by Jeff Jenness, Wildlife Biologist, GIS Analyst, US Forest Service, Rocky Mountain Research Station, 2500 S. Pine Knoll Drive, Flagstaff, AZ 86001, jeffj@jennessent.com

⁴ <http://gis.esri.com/arcscrips/scripts.cfm>

⁵ This extension was created on August 7, 1999 by X. Guillotin, guillot@esrifrance.fr

⁶ <http://gis.esri.com/arcscrips/scripts.cfm>

References

- Backwell, Lucinda, and Francesco d'Errico. 2001. From the Cover: Evidence of termite foraging by Swartkrans early hominids, in *Proceedings of the National Academy of Science* 98, pp. 1358-1363.
- Brain, C.K. 1958. *The Transvaal Ape-Man-Bearing Cave deposits*. Transvaal Museum: Pretoria.
- Brain, C.K. 1968. Who killed the Swartkrans ape-men?, in *South African Museums Association Bulletin* 9, pp.127-139.
- Brain, C.K. 1969. The probable role of leopards as predators of the Swartkrans australopithecines, in *South African Archaeological Bulletin* 24, pp. 170-171.
- Brain, C.K. 1970. New Finds at the Swartkrans Australopithecine site, in *Nature* 225, pp. 1112-1119.
- Brain, C.K. 1974. A hominid skull's revealing holes, in *Natural History* 83, pp. 44-45.
- Brain, C.K. 1981. *The Hunters or the Hunted?: An Introduction to African Cave Taphonomy*. The University of Chicago Press: Chicago, London.
- Brain, C.K. 1993. Introduction, in C.K. Brain (ed.), *Swartkrans: A Cave's Chronicle of Early Man*, pp. 1-5. Transvaal Museum: Pretoria.
- Brain, C.K. and Pat Shipman. 1993. The Swartkrans Bone Tools, in C.K. Brain (ed.), *Swartkrans: A Cave's Chronicle of Early Man*, pp. 195-215. Transvaal Museum: Pretoria.
- Brain, C.K. July 29, 1999. Personal communication.
- Clark, J.D. 1993. Stone Artefacts Assemblages from Members 1-3, Swartkrans Cave, in C.K. Brain (ed.), *Swartkrans: A Cave's Chronicle of Early Man*, pp. 167-194. Transvaal Museum: Pretoria
- de Ruiter, Darryl J. and Lee R. Berger. 2000. Leopards as Taphonomic Agents in Dolomitic Caves - Implications for Bone Accumulations in the Hominid-bearing Deposits of South Africa, in *Journal of Archaeological Science* 27 (8), pp. 665-684.

Harris, Trevor M. and Gary R. Lock. 1996. Multi-dimensional GIS: exploratory approaches to spatial and temporal relationships within archaeological stratigraphy, in *Interfacing the Past: Computer Applications and Quantitative Methods in Archaeology CAA95 Volume II*, pp. 307-316. University of Leiden: Leiden.

Intergraph. 1994. *MGE Voxel Analyst (MGVA) User's Guide*, p. 6-14. Intergraph Corporation: Huntsville.

Jones, C.B. 1989. Data structures for three dimensional spatial information systems in geology, in *International Journal of Geographical Information Systems* 3 (1), pp. 15-31.

Mitchell, Andy. 1999. Mapping density, in *The ESRI Guide to*

GIS Analysis Volume 1: Geographic Patterns & Relationships, pp. 69-85. ESRI Press: California.

Raper, Jonathan F. 1989. The 3-dimensional geoscientific mapping and modelling system: a conceptual design, in Jonathan F. Raper (ed.), *Three dimensional applications in Geographical Information Systems*, pp. 11-19. Taylor & Francis: London, New York, Philadelphia.

Turner, A. Keith. 1989. The role of three-dimensional geographic information systems in subsurface characterization for hydrogeological applications, in Jonathan F. Raper (ed.), *Three dimensional applications in Geographical Information Systems*, pp. 115-127. Taylor & Francis: London, New York, Philadelphia.

Figures

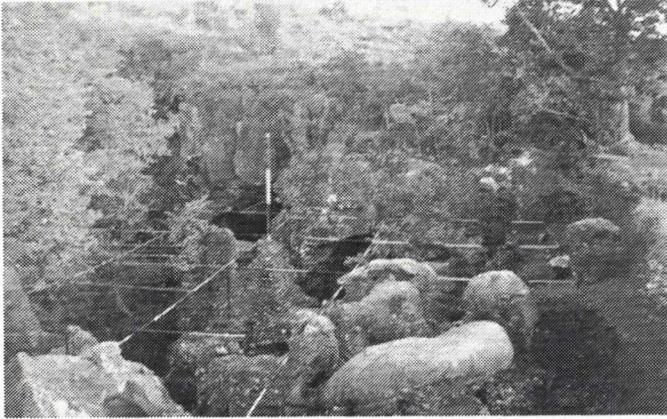


Figure 1. View of Outer Cave area of Swartkrans looking NW with metal excavation grid in place. Photo by Joseph Nigro.

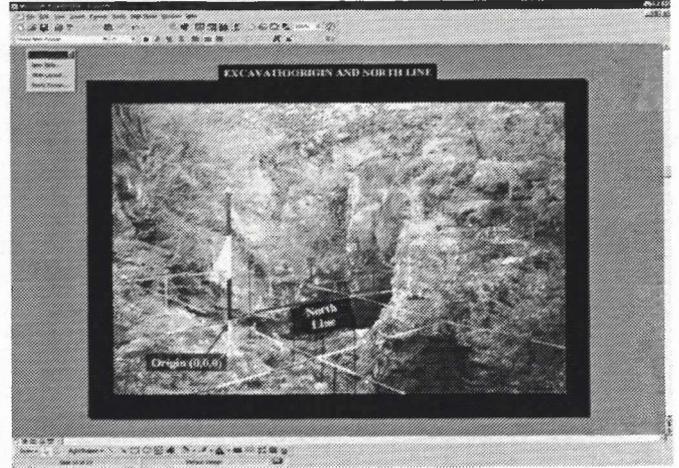


Figure 4. The origin and North line of grid used during the excavations and the survey. Photo by Joseph Nigro.

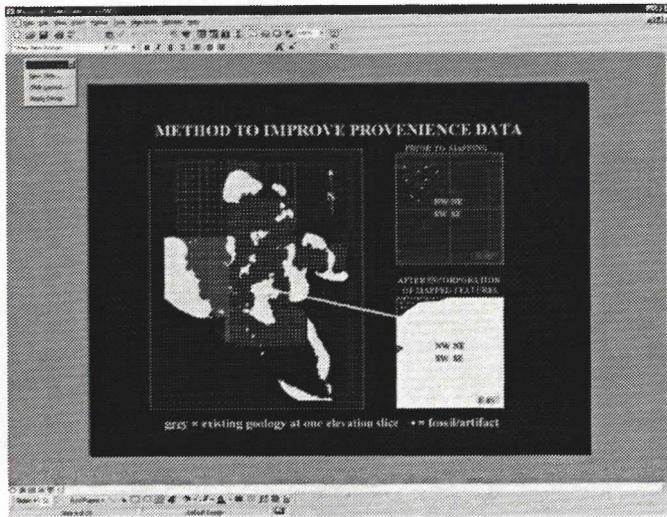


Figure 2. Arcview image depicting one elevation level of Swartkrans and the methodology used to increase the provenience of the fossils and artifacts. Image by Joseph Nigro.

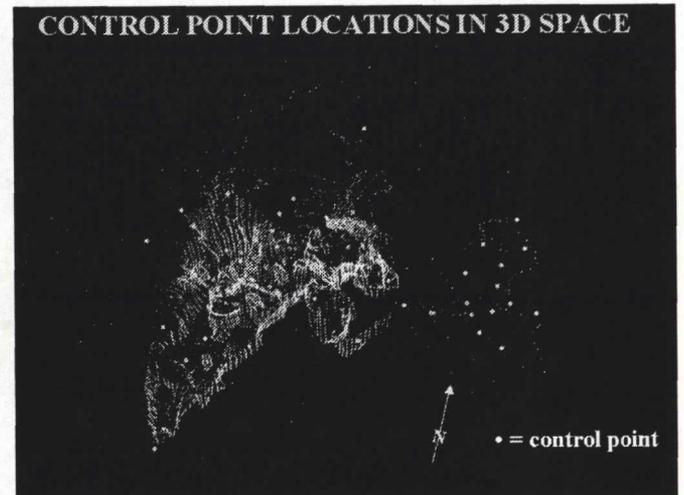


Figure 5. The control points established during the survey in 3D Analyst. The points shown in white represent the surface of the site. Image by Joseph Nigro.



Figure 3. The Wild T1010™ theodolite with a Leica Distomat™ Laser EDM. Photo by Joseph Nigro.



Figure 6. Examples of the differences in feature topography dictating the mapping interval. Photo by Joseph Nigro.

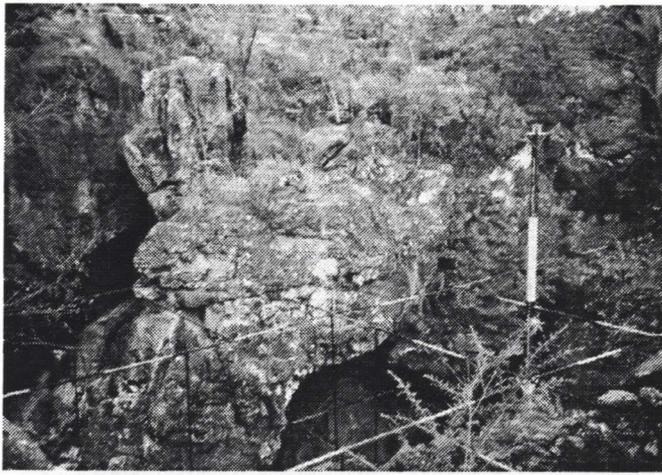


Figure 7. Example of a natural geological overhang, represented by a portion of the Hanging Remnant. Photo by Joseph Nigro.

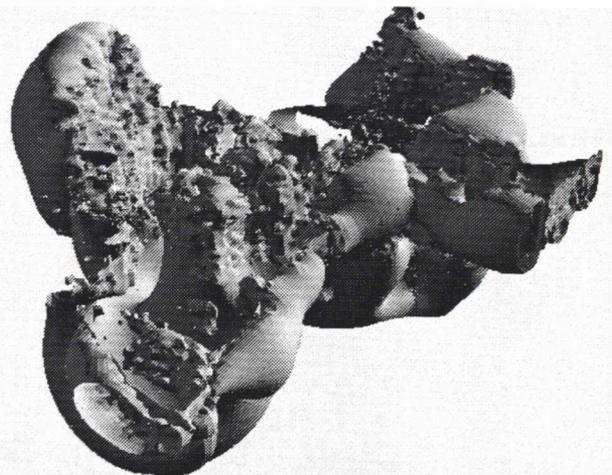


Figure 10. Image of Swartkrans in 3D Analyst, looking NW into the cave. The "bulbous floor" can be seen at the bottom of the image. Image by Joseph Nigro.

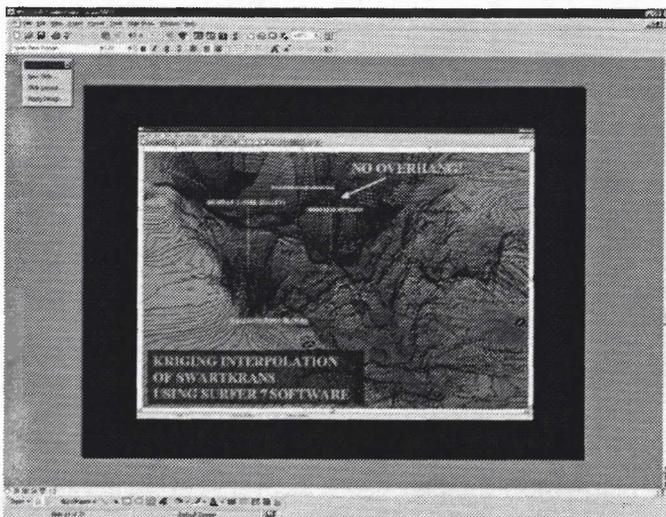


Figure 8. Interpolated image shown in 3D view using Surfer 7. The blue arrow identifies the data spikes produced. Image by Joseph Nigro.

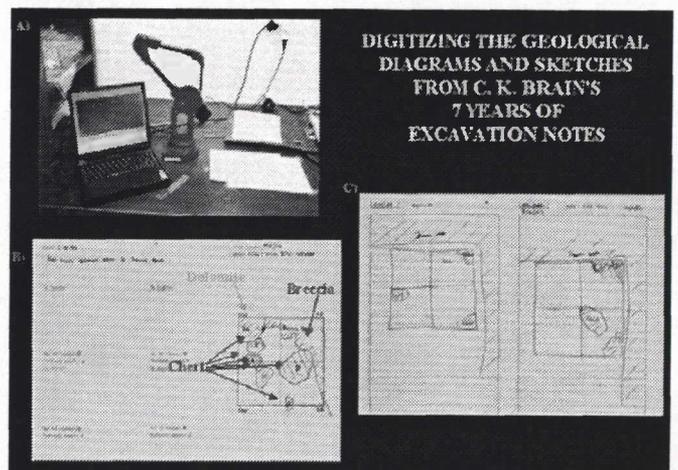


Figure 11. a) The Microscribe digitizer b) Excavation notes including a standard diagram c) Excavation sketch. Photo by Joseph Nigro. Excavation pages by C.K. Brain.

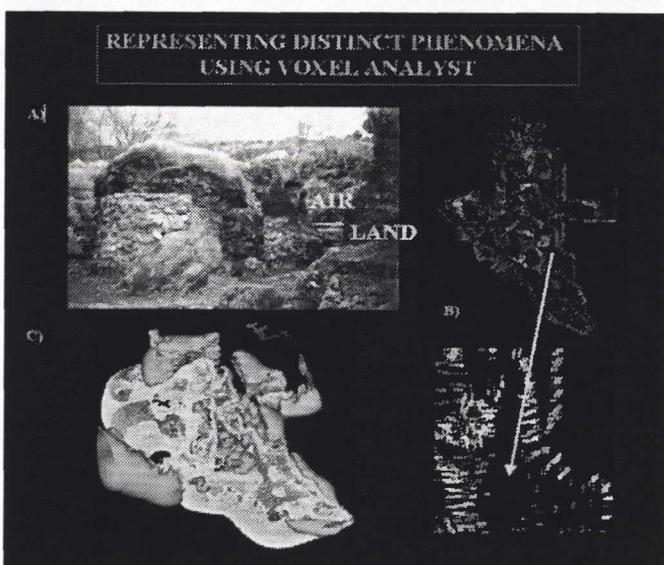


Figure 9. a) The air and land component that make up the site representing two distinct phenomena. b) The survey points in 3D Analyst with brown depicting the land and blue depicting the air c) the interpolated land and air volumes in Voxel Analyst. Photo and images by Joseph Nigro.

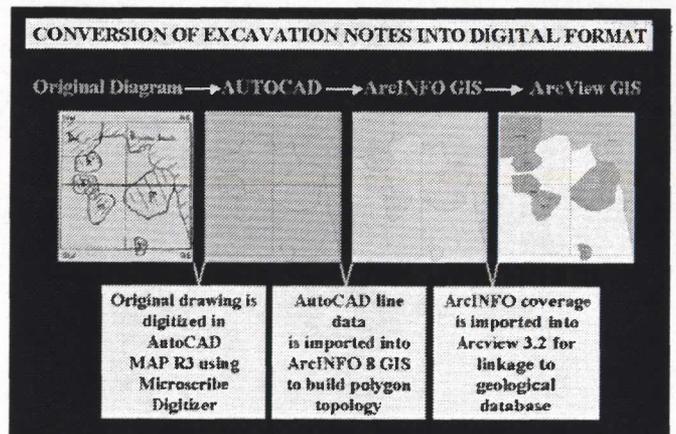


Figure 12. Procedure used to convert the excavation diagrams and sketches into digital form.

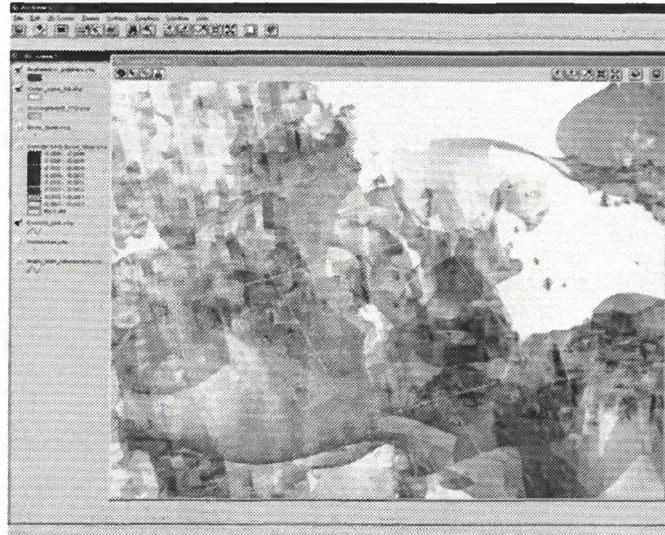


Figure 19. A sample of waterworn pebbles (red) viewed within the context of the surrounding cave (semi-transparent gray) using 3D Analyst. Image by Joseph Nigro.