

Mapping the past: GIS and intrasite spatial analyses of fossil deposits in paleontological sites and their applications in taxonomy, taphonomy and paleoecology

Gáspár Albert, Gábor Botfalvai, and Attila Ósi

ABSTRACT

At paleontological excavations, the use of digital surveying tools is becoming more frequent to measure the geographical location of specimens. This technology infiltrates into the discipline of paleontology from archaeology, where the mapping methodology is quite similar, and the GIS as a standard tool for analysis is more widespread. The result of such a survey is a geodatabase, which forms the basis of subsequent analyses. The workflow is represented as the: 1) surveying, 2) database building, and 3) spatial analysis creating maps or 3D models. The presented methodological paper describes the details of the workflow, explaining the best practices and highlighting those issues which are necessary to be targeted even on the field. The methods tackle the optimal database structure, the spatial querying, which is managed from simple data table formats, and the 3D modelling. Explanations for these topics are given throughout specific programs; however, the tasks are also described generally enabling the reader to apply the described method to other programs. The data structure is explained through Excel worksheets, and for the analysis, an Excel-based macro script was developed, which is published as a supplementary material of this paper. Complex spatial analyses and visualization were done with Jewel Suite, a geological 3D modelling application. Demonstrating the workflow, three types of taphonomical inquiries are discussed using the surveyed materials of the Santonian dinosaur bed at the Iharkút site (Hungary). This technique is easily applied and becomes an important tool to obtain more precise taxonomical, taphonomical, and paleoecological interpretations in fossil excavations.

Gáspár Albert. Eötvös Loránd University, Department of Cartography and Geoinformatics, Pázmány Péter prom. 1/A, Budapest, 1117, Hungary. albert@ludens.elte.hu

Gábor Botfalvai. Hungarian Natural History Museum, Department of Palaeontology and Geology, Baross st. 13, Budapest, 1088, Hungary; Eötvös Loránd University, Department of Physical and Applied Geology, Budapest, Pázmány Péter prom. 1/C, Budapest, 1117, Hungary; and Eötvös Loránd University,

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Department of Paleontology, Pázmány Péter prom. 1/C, Budapest, 1117, Hungary.
botfalvai.gabor@gmail.com

Attila Ősi. Hungarian Natural History Museum, Department of Palaeontology and Geology, Baross st. 13,
Budapest, 1088, Hungary and Eötvös Loránd University, Department of Paleontology, Pázmány Péter
prom. 1/C, Budapest, 1117, Hungary. hungaros@gmail.com

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INTRODUCTION

In vertebrate paleontology, mapping of specimens is a key activity during excavation, because the original positions of the buried fossils provide essential information about the depositional history of the bone concentration, and it cannot be reconstructed after removing the fossils from the bonebed. However, the mapping of specimens during the excavation is a time-consuming activity, and the building of a meter-grid system can be complicated in the case when the mapping is done on an irregular surface (e.g., Abler, 1984; Organ et al., 2003; Britt et al., 2009). Although putting the recorded data into a database and constructing digital maps make the process more complicated, a well-constructed digital map provides indispensable data that can be used to interpret the depositional conditions at the time the assemblage was concentrated and buried (Eberth et al., 2006; Jennings and Hasiotis, 2006).

From taphonomical aspects, recording the position, size, and orientation of fossil bones (referred as “bone mapping”) is especially informative. Over the last decades, our knowledge about the dispersal and depositional modes of the transported bone materials continuously increased due to several field and laboratory studies (e.g., Badgley, 1986b; Behrensmeyer, 1978; Dodson, 1973; Kaufmann et al., 2011; Lyman, 1994; Voorhies, 1969 and references therein). These works provide useful information about the preservation, transport, and burial of bones and other skeletal specimens, and can be applied to understand the processes which created the fossil bone concentrations.

Despite the growing taphonomical knowledge, the methodology and usability of the outcrop-scale fossil mapping has changed only in small increments during the last decades. The meter-grid system and the measuring tape (e.g., Alberdi et al., 2001; Eberth et al., 2006; Rogers, 1990) are still

the most commonly used techniques for mapping specimens in paleontological sites, in spite of the more usable and more precise surveying devices modern surveying technology has developed (for example: total stations and geodesic GPS). These tools make it possible to quickly record the lateral and vertical position of all specimens with the same (or higher) precision, as the traditional metric grid can provide with a measuring tape. Either way, the positions of the collected elements are measured, and the spatial relations can be analyzed with programs if the data are recorded in a database.

The geographic information system (GIS) is a useful tool for analyzing the spatial distribution of the collected specimens. It consists of a database and a program (e.g., ArcGIS, QGIS, GRASS, MAPINFO), which can run queries and display the spatial data in a map form. Application of GIS is already widespread in archaeology for the very same purpose as it can be of use in paleontology: to help mapping specimens (Rayfield et al., 2005; McCoy and Ladefoged, 2009; Reed et al., 2015). It also helps to evaluate the mapping data in order to show relationships (using statistic methods) in the bone material, which remain hidden during visual interpretation. The importance of spatial technology in the interpretation of paleontological and archeological data has long been recognized and can be classified into three categories: data management, visualization, and spatial analysis (Harris and Lock, 1995; Goodchild et al., 1992; Breithaupt et al., 2004; Katsianis et al., 2008; McCoy and Ladefoged, 2009; Wheatley, 1995; Wheatley and Gillings, 2003; Anemone et al., 2011 and references there in). Also, several mapping techniques were developed characterizing the processes which influenced the formation of the excavated site (e.g., Jennings and Hasiotis 2006; Anderson and Burke, 2008; Benito-Calvo and de la Torre, 2011; Gallotti et al., 2011; de la Torre and Benito-Calvo, 2013; Bertog et al., 2014; Birkenfeld et al., 2015; Giusti and Arzarello, 2016 and reference

there in). Archaeologists have already implemented quantitative methodologies in order to evaluate the measured data (e.g., Nigro et al., 2003; McPherron, 2005; McCoy and Ladefoged 2009; Anderson and Burke, 2008; Houshiar et al., 2015; Giusti and Arzarello, 2016 and references therein), but in paleontology these methods are infrequently applied, and researchers rather relied on the visual interpretation of bone distributions for the identification of spatial patterning within paleontological levels (Eberth et al., 2006). This phenomenon probably can be explained because the paleontological sites usually represent a broader time interval, and the sedimentological, taphonomical, and taxonomical data are more incomplete and less reliable for the quantitative analyses (Oheim, 2007). Yet, there are a few examples, where high-precision surveying devices were applied during the excavations, and the mapped data were evaluated by GIS and statistical software packages (e.g., ArcGIS, SAS, BDMP) in order to facilitate taphonomy studies (Alberdi et al., 2001; Bertog et al., 2014; Bramble et al., 2014; Jennings and Hasiotis, 2006; Lacruz et al., 2003), or fossil site predictions (Oheim, 2007). These paleontological examples do not include detailed descriptions about the implementation of statistical methods, but suggest that the use of GIS allows paleontologists to complete more accurate quantitative analyses of spatial relationships pertinent to taphonomic interpretation. Although, in the listed examples the authors refer to their approach as a 3D analysis, some of the cited software packages have only limited capacity in 3D spatial statistics (e.g., ArcGIS, ArcScene), projecting the 3D data on surfaces or planes. Thus, the spatial nature of the collected data could not be fully exploited. Methods of GIS based true 3D modelling, which exploits the spatial variables, may comprise explicit and implicit modelling (Maxelon et al., 2009). Explicit methods aim for a 3D representation of the measured data in a virtual environment in order to explain the outcrop geometry, stratigraphy, and orientation of the observed phenomena, from 3D aspects. The model is a result of iterative work processes, where the geometrical elements are placed deterministically in the virtual environment by the modeler manually or semi-automatically (Breunig, 1999; Kaufmann and Martin, 2008). Implicit modelling methods use the Euclidian coordinates (x , y , z) and the qualitative or quantitative attributes of the findings as geostatistical variables to produce estimations on the locations where measured data are not

available (Breunig, 1999; Kaufmann and Martin, 2008).

In geosciences the explicit and implicit methods are usually combined with each other using the geodatabase of primitive (i.e., points, vectors) and complex (like surfaces, blocks) spatial structures; furthermore the analysis is not limited to surfaces or vertical planar sections (Calcagno et al., 2006; Jones et al., 2009). Instead, the program, which performs the spatial query, works with the tessellation of volumetric elements (volume pixels or *voxel/s*), the size of which define the spatial resolution of the model (Jessel, 2001). Each voxel usually has an hexahedral shape and is associated with a record in the background database containing several attributes. When such a modelling system is applied, one can perform multivariate statistical methods to estimate the unknown attributes of a spatial position (assigned to a voxel) using the geometry of the known locations (i.e., the voxels where measured data can be found). Depending on the used mathematics, the results will differ from each other, but all of them are considered as estimations inevitably bearing uncertainties (usually referred to as the error of the modelling method). The modelers' responsibility is to select the method producing the smallest error.

The aim of the present study is to give an insight into the usability of the spatial analysis in fossil mapping and explain the methodology of the used programs. In contrast to the previously mentioned studies it explains the workflow of the whole process in details, which should be followed to build a working GIS from the recorded specimens. The geodatabase, and the modelling methods described in the paper are created to utilize them in the most common taphonomical analyses. Demonstrated by the 3D mapping of a bone-yielding bed of the Late Cretaceous vertebrate locality in Iharkút, Hungary, the presented methods allow the production of simultaneous or separate visualizations of the original data or the modelled results and analyses of the fossils within their original spatial contexts. They also permit intrasite spatial analyses that allow a comprehensive investigation of the site formation processes. Both traditionally measured and digitally surveyed data can be processed this way if the precision of the data makes it possible.

WORKFLOW OVERVIEW

Working with the collected paleontological data of an excavated site requires constructing an information system (analogue of a GIS), which has

three main functionalities from the aspect of data management: 1) processing; 2) storing; and 3) representation. All of these functionalities (Table 1) are handled with different component programs, since such complex program suites do not exist for paleontological purposes yet. The component programs of the GIS must be able to communicate with each other via import-export file types or direct database connections. Although, using various programs makes the process complicated, the flexibility of the components allows one to create a workflow, which leads to the overall aim: a high resolution spatial model of the site with database background.

Such a workflow is presented here to facilitate the spatial analysis of paleontological data that have been measured either with traditional or modern surveying tools. It includes two component programs: *Excel* with *Visual Basic* scripts mainly for the processing and storing functionalities, and *Jewel Suite* modelling program for the visual representation. The result of the workflow is a GIS allowing one to create models and draw conclusions from the spatial analyses. The types of analyses are varying depending on the goal of the modeler, but basically taphonomical and taxonomical models can be derived from the data. However, the method is applicable only if the collected data were mapped and all the findings have spatial position measured with a precision of a few centimeters.

Measurement Processes at the Site

From the aspect of spatial analysis, mapping the exact position of bones and other findings at the site is crucial, because after removing the fossils their accurate positions are not available anymore. The planning of such activity should be defined stepwise to avoid loss of data. If tapho-

nomical analysis from the findings is also planned, not only the fossils, but the layer boundaries (top/bottom) should be measured, along with the fossil's vertical position relative to them. The findings overlaying each other in the beds obviously will have the same x, y (horizontal coordinates in a Cartesian system), so measuring only the horizontal geographical parameters is not enough; a third coordinate should be added (elevation or vertical distance from the top of the layer). Defining a Cartesian coordinate system at the site may occur physically (grid of ropes and spikes), or virtually (geodesic methods); also the two of them can be combined.

The meter-grid (box-grid) system is the most commonly used technique for mapping specimens in a quarry, and it can produce the proper resolution for GIS-based analyses. It is quite adequate if the site is flat and relatively small, and easy to record the locations of the findings by measuring their horizontal distances from the grid nodes (e.g., Abler, 1984; Botfalvai et al., 2017; Britt et al., 2009). However, this technique is an invasive method and involves several difficulties when paleontologists try to use it on rough terrain. For example: (1) the spikes hammered into the quarry floor as grid nodes can destroy the buried bones when beaten into the layer (Organ et al., 2003); (2) if the site is situated on a hillside or on uneven ground surface, building the grid is time-consuming and complicated; (3) measuring the vertical position of the findings is more problematic than measuring the horizontal coordinates. Although the invasiveness can be avoided with the "floating-grid" system presented by Chris L. Organ and his colleagues (Organ et al., 2003), it is even harder to set it up on steep slopes. Furthermore, the traditional meter-grid mapping method is unusable if the bonebed is

TABLE 1. The main functionalities of a modular GIS constructed for spatial analysis (Albert, 2017).

Functionalities	Description
Processing	The data processing tool is responsible for the digital recording of text (notes, reports), alphanumeric and logical (true/false) information, images (photos, scanned documents) and vector-geometry (line-plot maps, sections).
Storing	Data storage tools provide secure data store and make it possible to reach data in digital form, which is located on mass storage devices in its appropriate format. The storing is maintained and accessed via database and file management tools.
Representation	The tool that represents the data as a 2D map or a 3D model is a complex application, which not only visualizes the data, but most often serves as the GIS environment. It makes possible to access not only the visual representation of the data, but all the collected information from the database providing a user interface for spatial analysis.

expansive (several hundred meters long and wide) and its fossil-content is sparse and scattered.

Using high precision geodesic devices such as total stations (computerized theodolites), or real-time kinematic (RTK) GPS has already become widespread at archaeological and paleo-anthropological excavations, gradually replacing the analogue meter-grid method (Neubauer, 2004; McPherron, 2005; Roosevelt et al., 2015; García-Moreno et al., 2016), but they are used only at a few paleontological sites (Bertog et al., 2014). Since the excavation techniques are quite similar in these disciplines, the modern surveying devices are of great use for paleontologists too, and the advantage of precise geolocation is already acknowledged in prospecting new sites (Anemone et al., 2011; Oheim, 2007). Although these methods are flexible enough to handle multiple approaches to excavation, and survey the position of fossils very quickly and easily without meter-grid system, both techniques have advantages and disadvantages. If total station is used, the surveying can be done even in covered sites (under a roof or inside a cave), but handling the instrument and the measuring rod requires two persons, and it takes 5–10 minutes to put a record correctly into the database. Measuring with an RTK GPS is quicker (it takes only 2–5 minutes to record one finding), and it is handled by one person, but it relies on the Global Navigation Satellite System (GNSS) and the GSM network, and thus, it can be used only in open areas. The precision of such surveying tools is within a few centimeters both horizontally and vertically, and after connecting them to a portable computer, the collected data can be processed even on the site. Using these surveying methods at excavations that are separated from each other, the uniform geodesic coordinates allow paleontologists to analyze the spatial relations of findings from multiple locations.

However, during a measurement one has to record several attributes of the fossil with the surveying device, if the overall goal is to create a complete database on the site.

Database Structure

The direct digital recording of observations at the time and location of actual excavation has a great priority, because the missed measurements are often irreplaceable after the excavation. Yet, the digital surveying procedure can be more time consuming than it is expected, extending the recording time of one single fossil with the descrip-

tion of several parameters (type, size, preservation, orientation, etc. see Supplementary 1). Slow surveying may halt the excavating process, so it is important to find the optimal data structure, which is detailed enough to contain the necessary information, but easy to record it quickly with the surveying device. Reed et al. (2015) address this problem as the main challenge of the piecewise mapping of fossils. They also provide recommendations for a paleoanthropological database standard (PaleoCore), which is built on free and open source technology. However, a database structure optimal for post processing (e.g., statistical analysis), is not always useable on the field.

The technical requirements of the surveying program, which runs on the used instrument, usually predefines the possibilities regarding the complexity of the data structure, but the overarching goal – to record it quickly – is common. The aim of the surveyor is to record as many pieces of information as possible in the shortest time, but the technique to achieve this can be different depending on the customizability of the surveying program running on the controller unit of the recording device; the following cases are the most common:

1. The program can handle multiple data fields and pre-defined dropdown lists, which help the surveyor to select the proper data types quickly.
2. The program handles several data fields but no dropdown lists.
3. The program can handle less data fields than the number of different data types, which are planned to be recorded.

The first is the optimal case, and there is a tendency that it will become widespread in the future. However, the second and third cases are common for most devices fabricated in the last two decades. To facilitate the recording, the usual method in these cases introduces abbreviations/codes (Table 2) for the data categories which can be quickly typed in even on the field.

The codes can be concatenated to each other when recording them, thus enabling one to use only one database field for different information. If the method was used properly, the different data types can be reconstructed easily from the reduced database after downloading them to a computer. Subsequently the separated data is uploaded into a relational database (RDB) as contents of separate data fields (columns). To set up and maintain a GIS such RDB is necessary to construct, because it will provide the source data for the spatial analyses.

TABLE 2. Possible abbreviations/codes and their explanations used in a paleontological excavation site for quickly recording the information in the surveying device. The concatenation of codes in one single entry can be the following: B002_AN_B_2_121.

Identification code types	Codes	Explanation
Category and serial numbers	B001, T001, C001, E001; r01	One digit code of the category combined with the serial number of the finding of the certain category (e.g., B=bone, T=teeth, C=coprolite, E=else; r=stratigraphic element)
Groups	AN; P; E; PT; etc.	One or two digit codes of different taxonomical groups that were already described/expected to be find on the site (e.g., A=Anura; P=Pisces; E=Eusuchia; PT=Pterosauria)
Types	B; F; L; O; BF; OF; etc.	Maximum three-digit-long unique code of the anatomical type of the finding (e.g., B=bone; F=femur; L=limb bone; O=osteoderm; BF=bone fragment; OF=osteoderm fragment).
Size	1 – 5; 1 – n	Size of the findings in absolute or – alternatively – in relative terms.
Documenter	Unique id. (e.g., 121)	The unique identifier of the paleontologist/working staff member who excavated the fossil (or alternatively the identifier of the place, where the fossil was found).

Application of the Method in the Field

During the excavation of the Late Cretaceous (Santonian) bonebed of the Iharkút vertebrate site (Hungary) (Ósi et al., 2012), in the summers of 2014–2016 a Spectra Epoch RTK GPS was used to record the position of fossils (Figure 1). Its controller PDA unit was equipped with Windows mobile platform and the customization of the data structure was limited, so reduction of different data types into one entry field – as described above – was necessary. All the teeth, bones, and coprolites were separately measured by their coordinates. In addition, any features of specimens (e.g., size, taxonomical position, and anatomy) were also documented along with their positional data



FIGURE 1. Excavation site of the Santonian bonebed of Iharkút (Hungary). 1) Surveying staff member handling the RTK GPS unit. 2) The excavation site. 3) Using the controller PDA unit of RTK GPS for recording the different data of the measured fossils.

(Supplementary 1). These characteristics were coded as numbers or as uniform abbreviations in the generated database. Furthermore, top and bottom of the bonebed layer were also measured in different points during the excavation in order to provide explicit information about the bonebed geometry.

After three weeks of surveying, the database of the fossils was reconstructed in Excel and sorted into four data tables (worksheets): 1) records of all findings; 2) taxonomical groups; 3) anatomical types, and 4) size categories. Each year the database was updated with approximately 900 new measurements. The measurements of the stratigraphic unit's top and bottom layer made up a fifth data table (Figure 2).

Evaluation of the Measured Data

The reconstructed database was simple enough to manage it in Excel, and most of the querying and summing tasks do not require special knowledge in data management. However, some of the spatial querying tasks made it necessary to create customized macros as part of the database file. Excel contains a script editor interface, which facilitates the writing of sub-routines (macros) and functions in Visual Basic programming language. The created program code will be an organic part of the Excel file and can be executed as a macro; though, one has to allow the program to open files with macros to reach this functionality.

The connection between the data tables was defined via the "IF" and the "LOOKUP" functions of Excel, and a few macro scripts. The macros were

Columns of the „findings” data table

X	Y	Z	Code	Area	Group_code	Type_code	Size	Orientation	Note	Year
544376.3	210661.6	355.2	2013_1_4	1	T	PLF	2			2013

Group_code	Group	name	taxon
T	Testudines	turtle	ordo

Columns of the „group” data table

Type_code	Type
PLF	Plastron fragment

Columns of the „type” data table

Size	Category
1	<1.5 cm
2	1.5-5.0 cm
3	5.0-8.0 cm
4	8.0-16 cm
5	16< cm

Content of the „size” data table

X	Y	Z	Code	Type	Year
544372.1	210663.2	354.1	2016_r01	ra	2016

Columns of the „geometry” data table

FIGURE 2. Data tables (worksheets) of the relational database reconstructed in Excel from the surveying file. The arrows indicate the linking fields between the tables. Note that the “geometry” table containing the base and top layer positions is not connected to the other data tables in Excel. (see Supplementary 1.)

developed to run complex spatial queries in the database answering the following questions:

1. How many other – possibly similar – findings are located around the fossils of a given (or more) taxonomical group(s) within a defined buffer zone?
2. How many findings with similar/different anatomical types are located around a given (or more) taxonomical group(s) within a buffer zone?
3. What is the optimal resolution of a 3D grid model aimed to represent the spatial distribution of the findings?

Furthermore, the macros provided the connection to the 3D modelling component program (Jewel Suite) by formatting the query result into the proper data structure. The questions were answered with lists of fossils (identifiable by their ID code) and statistical data which can be visualized on maps and diagrams.

Data analysis within the Database

The database of the Iharkút vertebrate site between 2013 and 2016 contains 3892 records in the “findings” table (Supplementary 1). The geographic positions are defined in the Hungarian National Grid System (Mihály, 1996), which has served as the Cartesian coordinate system for the measurements. The taxonomical groups were defined into 30 and the anatomical types into 56 categories (see “type” worksheet in Supplementary data 1). The categorization of groups does not follow the taxonomical hierarchy because identification of a finding on the site depends on the preservation and preparation conditions of the fossil. The level of uncertainty is reflected in the use of “one fits for all” categories like Sauropsida (S) or even Vertebrata (V). Categories like this were also used describing uncertain anatomical types (e.g., bone as B).

When analyzing such diverse data, one has to consider the possibility that some of the differently identified specimens can belong to the same –

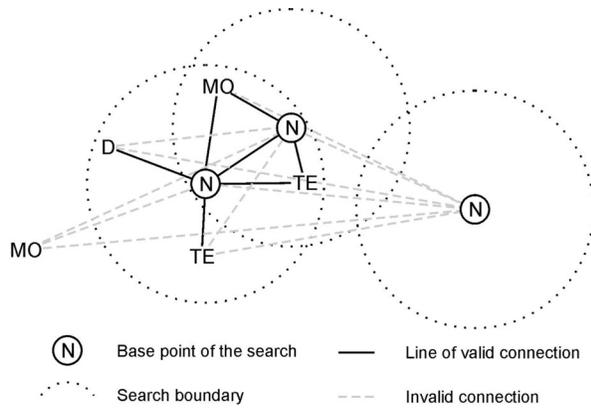


FIGURE 3. Geometry of a complex spatial query around three base points (N=Nodosauridae). The taxonomical groups to be searched are: D=Dinosauria, MO=*Mochlodon*, TE=Tetanurae, and the N itself. The result is one full and one partial match for the three base points. Identified possible connections are marked with continuous lines.

usually more specified – taxa, and even to the same carcass amongst the scattered remnants. The goal is to find out whether the well-defined findings can help to identify the fossils which may belong to the same carcass by running complex spatial queries on the database (Figure 3). Subsequently, the queried group of findings can be re-analyzed thoroughly. Such data analysis was han-

dled with a macro (Supplementary 1; GroupSelect) in the Excel file, which initialized a query form (Figure 4).

The form offers a multi-select list of taxonomical groups and the filtering option for specific anatomical types. Taxonomical groups can be selected as the geometrical base of the spatial search, and also a search list can be created from (different) groups. The script will look for the findings, which are in the search list and located within a specified buffer distance from the findings, defined as the geometrical base of the search. Using the form, one can work with external coordinate files too, allowing specifying locations of high interest manually as the geometric base of the query.

The result of a query can be exported as a new data table in column separated .txt file format (Table 3). The columns of this table are the followings: *finds*; *findType*; *Code_list*; *Xm*; *Ym*; *Zm*; *Code(base)*; *Code(finds)*. The detailed description of the file structure is given in the supplementary documentation (Supplementary 2).

Also, the query result can be exported as a 3D line-plot, which is of use in the visualization of the associated findings (i.e., as a map). The file format is .bln (simple ASCII type), which can be imported into standard GIS programs.

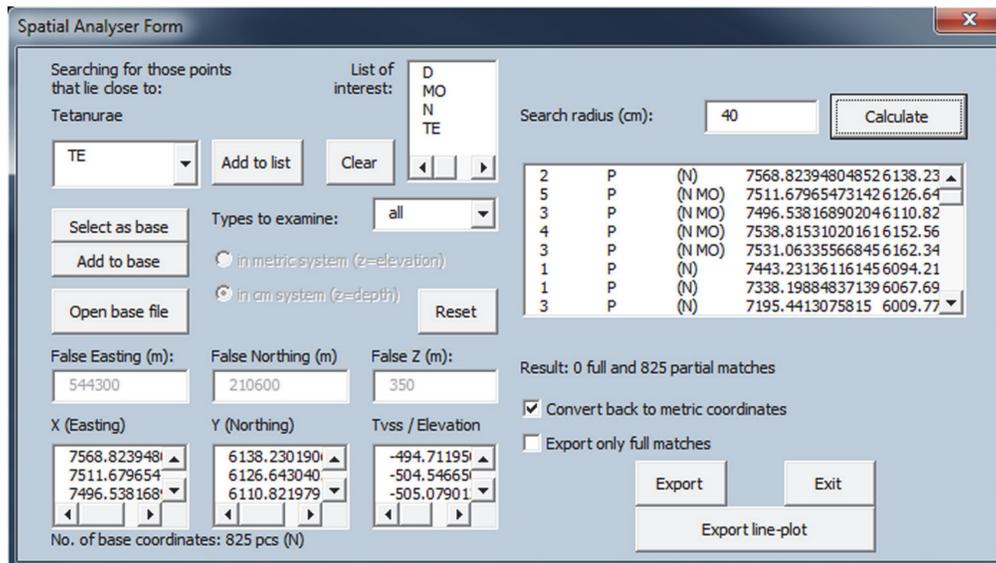


FIGURE 4. User Interface of the spatial querying macro (GroupSelect). The displayed query shows a selection of 825 findings from the taxonomical group of N as the geometrical base of the query. The macro searched for the matching cases regarding the taxonomical groups of D, MO, N and TE within 40 cm from the 825 base points. All anatomical types were examined. Full matches were not found, only partials were present meaning that at least one of the taxa in the list is identified within the specified sphere.

TABLE 3. Data types and explanations of the columns (fields) of the exported query-result data table.

Column name	Data type	Explanation
finds	Numeric (integer)	Within the given buffer distance (a 3D sphere), how many fossils were found around the concerning base point which belongs to one of the listed taxonomical groups, and has the appropriate anatomical type (if it was defined).
findType	Text	Category of the search result from the aspect of the listed taxonomical groups: E (empty); P (partial); T (total)
Code_list	Text	Group codes of the taxa that were found around the base point (one code may represent more matches from the same type).
Xm	Numeric	Easting of the meter-based geodesic coordinate system. (If the result is exported as a cm-based file for using it in JS this column is named as Xcm)
Ym	Numeric	Northing of the meter-based geodesic coordinate system. (If the result is exported as a cm-based file for using it in JS this column is named as Ycm)
Zelev	Numeric	Elevation of the meter-based geodesic coordinate system. (If the result is exported as a cm-based file for using it in JS this column is named as Zdepth)
Code(base)	Text	ID code of the base record (used as the center for the buffer search).
Code(finds)	Text	ID code(s) of the record(s) that was/were found around the base point.

Working with the Data in a 3D Modelling Environment

The familiar user interface of Excel made it possible to run spatial queries by paleontologists untrained in database management and study the properties of the results by numbers. However, the visual representation of the results was not available within this component program. For visualizing, and analyzing the results of the spatial queries, or the whole database, a different component program – JewelSuite (JS) – was used, which is capable of creating 3D stratigraphic and parametrized models. Furthermore, this program was capable to combine the results of the spatial querying with the explicit modelling methods based on the geometry measurements of the bonebed.

This component program is a full workflow framework that supports and describes every step needed to build complex 3D geological models (BakerHughes, 2017). The files are called “solutions” as they represent only one of the many solutions of a problem (like ‘where can I find the places which are within 30 cm from a certain type of object?’). When starting a new project in JS, one has to create and save a project file with an extension .jewel. This file contains the database and all the user settings associated with a given project, and when opening a .jewel solution file, one has access to all the geometric and parametric data stored in the database.

Although the program has its advantages in using built-in measurement units that can be con-

verted from one to another easily, it is not designed to create models with a few centimeter resolutions. The processed lharkút bonebed RDB was measured almost on sub-centimeter resolution with the RTK GPS. To avoid unwanted upscaling during modelling, the meter-based coordinate geometrical data was transformed to represent centimeters as base units prior to importing it into JS as meters. This was achieved with a trim of large numbers from the Easting, Northing, and elevation data and multiplying the result with one hundred. Additionally, since in JS the Z-axis in the modelling environment points downward and is called tvss (true vertical subsea depth), the elevation values were switched to negatives.

With the modelling program, the database of fossils is visualized in the 3D environment, and even this may help the paleontologists to understand spatial relations amongst the findings. For example selecting one or a few taxonomical groups to be visualized and hiding the others may reveal clusters of findings, triggering taphonomical insights. Using this basic functionality is not an act of real spatial modelling in a sense that new data are not created by mathematical methods. Modelling actions – creating estimations with the component program – can be the following in this sense:

1. New property is created for an already existing object using existing ones (e.g., geometry data is queried for the points containing their distance from the top and/or bottom layer of the bonebed).

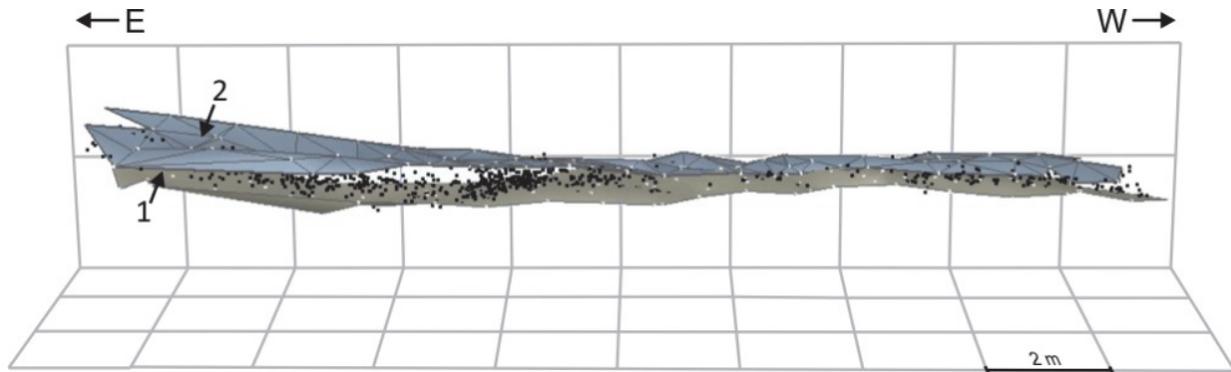


FIGURE 5. Stratigraphic model of the Late Cretaceous Iharkút bonebed (site SZ-6) seen from the North representing the base (1), top (2) layer boundaries and the findings (black dots).

2. Entity with higher complexity is created from base data having lower complexity (e.g., surface model from dispersed points, or volumetric model in between surfaces and/or around dispersed points).

Properties of an object are basically imported into the modelling program with the original database (like the codes of the taxonomical groups, the anatomical types, or the year of finding). The importing process, however, creates a copy of the original database, which can be extended with new fields (columns) but not connected anymore to the original database. The new properties are created via the *Property Calculator* sub-application of the modelling program.

The surface modelling is based on the measurements of the top and bottom layer of the bonebed. The records of the “geometry” data table are imported into the modelling program and models for the base and the top boundary surfaces are created via interpolation (Figure 5). The surface geometry can be a network of irregular triangles (TIN model) or a regular grid; the surface modelling method is an important element of the process, which has to be selected for the specific situation to achieve the minimum errors (Yang et al., 2004).

With the volumetric modelling, one specifies a void (modelling area) where the program will calculate estimations for those places where direct observations were not present. These calculations are usually interpolations and geostatistical estimating processes. It is also called implicit modelling (Calcagno et al., 2006). The model is composed of small tessellated cell units (voxels) each of them having their own (estimated or measured) properties. The size of these units specifies the 3D resolution of the model, and their shape is most often hexahedral (Figure 6). The center points of the cells – forming a spatial grid – are

defined as individual database records (rows in the data table). The volumetric model also gives information about the physical extent of the processed materials in cubic meters.

Both the surface and the volumetric modelling produce new geometry (exactly defined points of the surface and the voxels) in the modelling environment, which must be handled almost similarly as the records of the original database. This can be done only if the modelling program (such as the JS) is capable for GIS operations. In this case further analysis can be done in the modelling program. Alternatively the data of the new geometry (records of the grid nodes) are exported into a new database and are analyzed by the modeler using the functionality of an external program. Such possibility is also given in the workflow presented here, if one wishes to use the Excel macro with a text-type database file.

Calculating the Optimal Resolution of the 3D Model

The resolution of a volumetric model plays a primary role in the geostatistical processes. If too large cells are used (e.g., larger than the thickness of the bonebed), the varying original records will be averaged, and the most occurring parameters will dominate the results. On the other hand, if the cells of the model are too small, one original record will affect too many cells, creating unnecessary duplications. Furthermore, large resolution slows down the calculation processes, so it is best to avoid creating unnecessarily small voxels.

The optimal size of the grid resolution was calculated from the original database records using the Excel macro (GroupSelect) to create groupwise spatial queries. The following analysis created several new column-based data table as the result of the queries, each of them representing the number

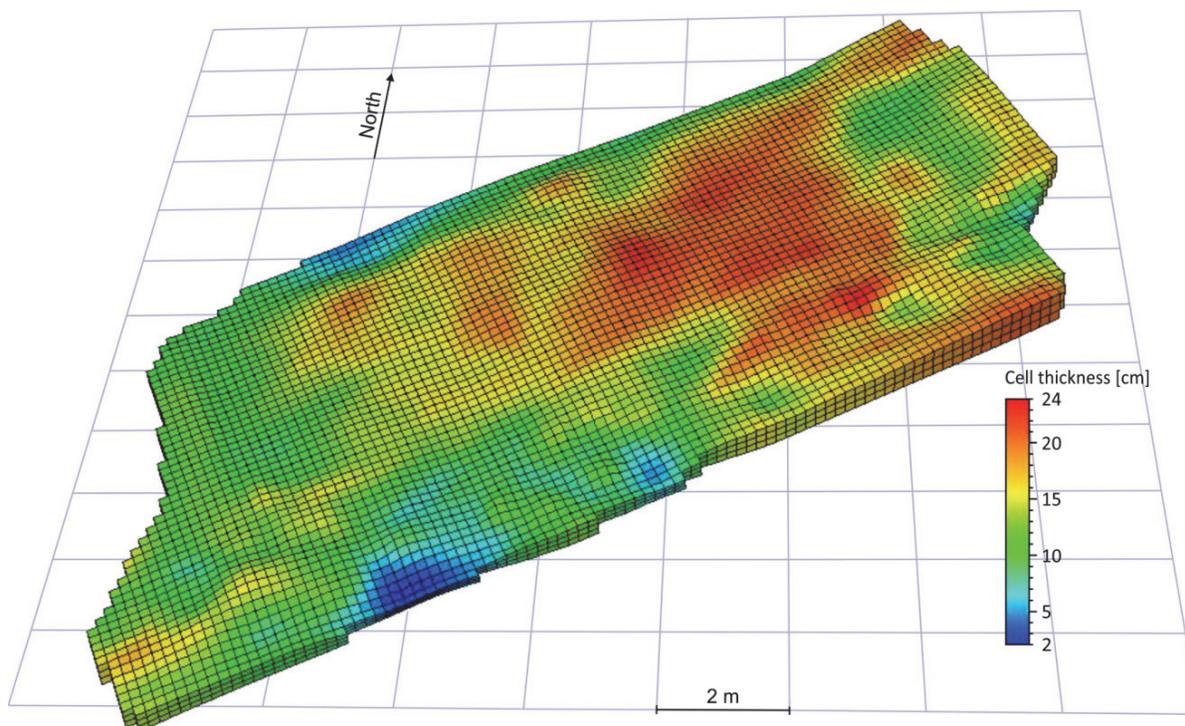


FIGURE 6. View of the volumetric model of the Late Cretaceous Iharkút bonebed (site SZ-6) from the South, coloured according to the vertical thickness of a single cell unit (voxel). The horizontal resolution of the model is 20x20 cm and separated into three inner layers.

of findings around the points of the selected taxonomical group in a defined buffer distance. These files contained the numbers of query matches in the “finds” column. With the repeated search of similar categories by modifying the search radius around the individual points of a specific taxonomical group from 10 to 100 cm with 10 cm intervals, one can compare the query matches (the database-files) to find an abrupt increase of the numbers. The initial value was one (since the center of the search was the first of the finds); those occurrences were counted where the increase of similar taxa was doubled relative to the previous interval (Figure 7). Using the richest bonebed of the Late Cretaceous Iharkút vertebrate locality (site SZ-6, see Botfalvai et al., 2015) as a case study, three taxonomical groups and the coprolites – having more than 600 records – were analysed, and the 10–20 cm interval which contained the most numerous “doublings” was selected as the cell size in the 3D grid. The interval distance is measured in all directions from the central node, making the possible cell size range 20–40 cm. As the smallest within this range, a 20 cm optimal grid resolution was selected for the 3D models. The vertical resolution, however, is varying between 2 and 24 cm

(Figure 6); for this the defining parameters were the total thickness of the bonebed and the number of internal layers. The analyzed taxonomical groups were the Nodosauridae, Testudines and the Sauropsida; the latter represents all those findings, which were not determined on the site more precisely.

UTILIZATION OF THE WORKFLOW MODEL

In the following subchapter, we introduce three different taphonomical inquiries related to the richest bone bed of the Late Cretaceous vertebrate site in Iharkút, western Hungary (Ősi et al., 2012), which can be done by using the component programs and standard GIS applications described in the previous sections. The first of these tackles the general spatial distribution of fossil content. The second one concentrates only on the bone materials and tackles the size distribution both horizontally and in the vertical profile of the bone bed. The third one concentrates on the probability of association among the fossil remains. The goal of this subchapter is to introduce the possibilities connected to the abovementioned workflow model, but the interpretation of these results for the Iharkút site will be summarized in a further manuscript

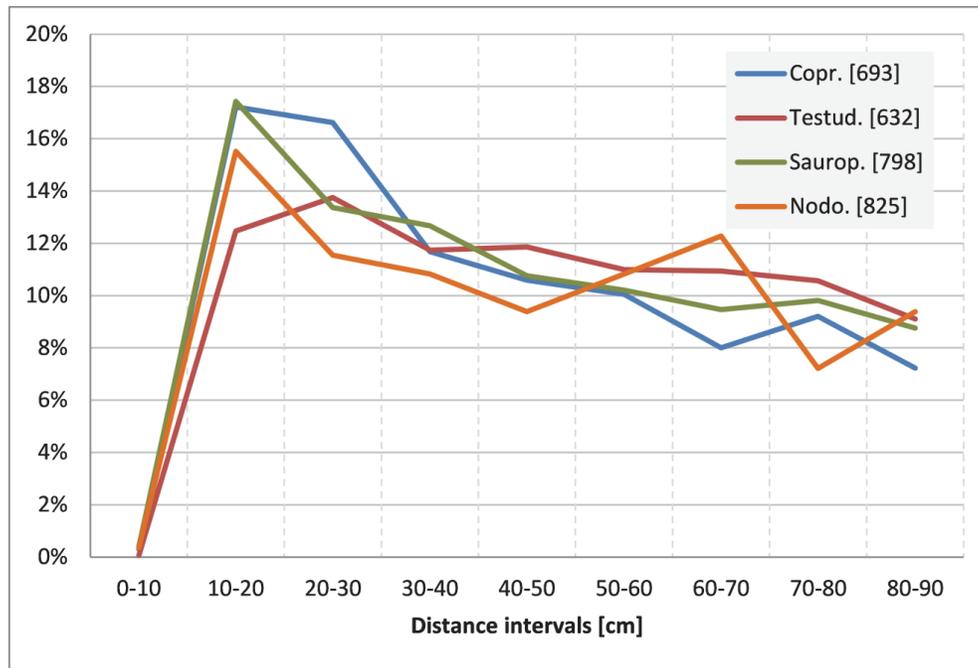


FIGURE 7. Relative frequency of doublings in the four most numerous groups (nodosaurid ankylosaur, turtle and sauropsid bones and coprolites) discovered in the Late Cretaceous Iharkút bonebed (site SZ-6), western Hungary. A doubling occurs when the increase of similar taxa was doubled relative to the previous distance interval. 12.5–17.4% of the doublings were registered in the 10–20 cm interval. The numbers in brackets indicate the counts of the group in the database.

focusing on the depositional mode of the vertebrate material (see Ósi et al., in press).

The Iharkút vertebrate locality, an open-pit mine in the Bakony Mountains (western Hungary), has provided a rich and diverse assemblage of Late Cretaceous (Santonian) continental vertebrates (Ósi et al., 2012). The isolated and associated remains represent at least 35 different taxa including fish, amphibians, turtles, mosasaurs, lizards, pterosaurs, crocodylians, dinosaurs, and birds. Sedimentological investigations by Botfalvai et al. (2016) pointed out that the fossil-bearing Csehbánya Formation in Iharkút has been deposited by an anastomosing fluvial system in a topographically low-level, wet, alluvial plain environment. The most important fossiliferous layer in the open-pit mine is a 10–50 cm thick bonebed of site SZ-6, which was deposited during ephemeral high density flash-flood events probably triggered by episodic heavy rainfalls. The taphonomical investigations of the site SZ-6 were already conducted by Botfalvai et al. (2015). This work was based on the findings excavated earlier than the detailed GIS survey has started in 2014. The taphonomical analysis of the detailed survey is in progress, but as case studies, the major pro-

cesses, involving the GIS technique mentioned above, are described in the followings.

General Distribution of Fossil Content in 3D

While a traditional bone map – depicting an excavation site – may give an overview of the distribution pattern, true spatial analysis can be done only within a spatial database, where the findings have absolute (measured) and relative height attributes (calculated). Instead of simply using the measured elevation data, one can apply the theory of the “law of superposition” in the taphonomical analysis by using the relative positions of the findings. In our workflow model, this parameter is calculated in the JS modelling program using the modelled base surface. The result is exported as a text file from the modelling program. It represents an enhancement of the original database (Supplementary 1), because two new columns (data fields) are added to the “findings” table (*distFromBase* and *bedThickness*). The first contains the distances of all findings from the base layer, and the second indicates the local thickness of the bonebed for each finding. These attributes can be used in conventional GIS programs such as ArcGIS, Mapinfo or QGIS to analyze the data. The result of such analysis can be represented as dif-

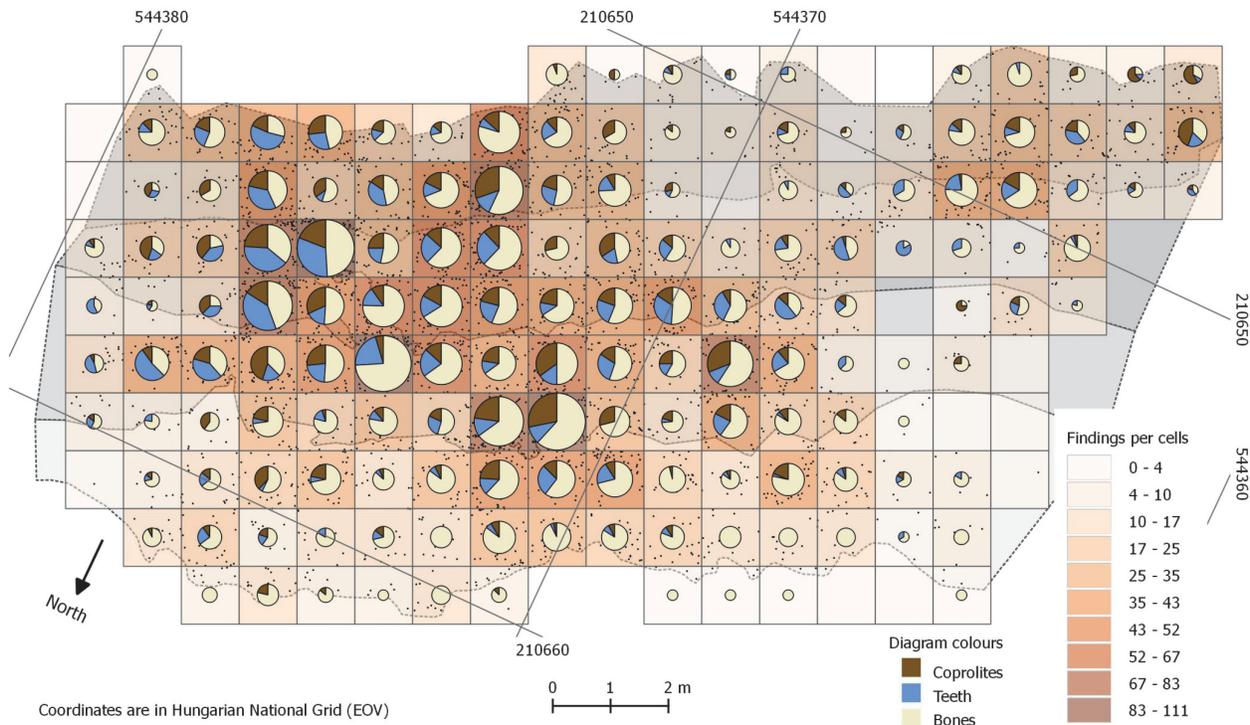


FIGURE 8. Density and diagram-map of all findings in the Late Cretaceous Iharkút bonebed (site SZ-6) during 2013–2016 excavations.

ferent maps of the whole bed (Gallotti et al., 2011). For example, the functionality of the QGIS 2.12 program was used to calculate the point density in each cell using point- and area-type features respectively (Figure 8). Furthermore, using the relative position data, maps for different vertical zones (inner layers) within the bonebed, can also be created.

The JS modelling program also provide tools for calculating the density of findings (Figure 9). These calculations are applied on the fine (20 by 20 cm horizontal, and 14.2 cm mean vertical) resolution of the 3D model, which is created in the modelling environment.

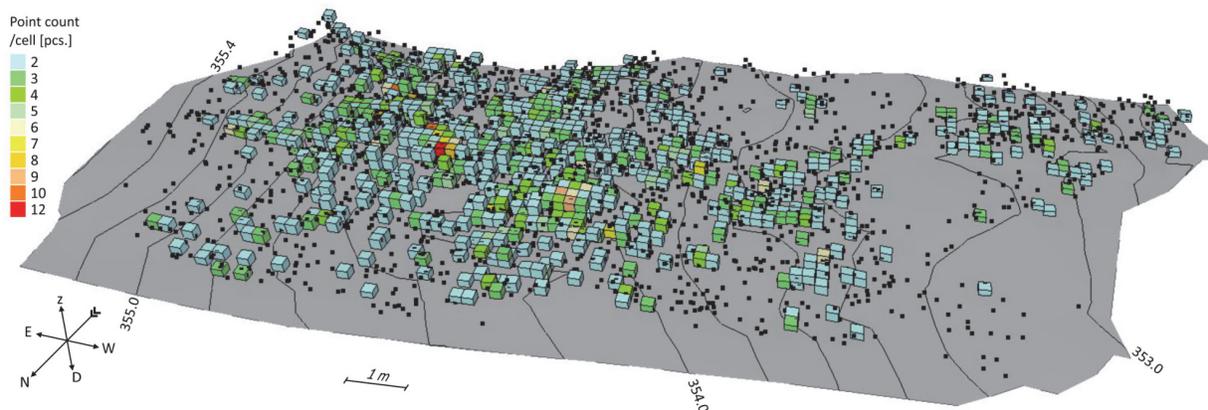


FIGURE 9. Visualization of the volumetric model of the bonebed at the Late Cretaceous Iharkút locality (site SZ-6), showing the density distribution of findings per voxels excluding the cubicles which contained only one fossil, or did not contain any fossils. Black dots are the locations of the findings; grey surface indicates the base layer with contour lines (20 cm intervals). The view is from a NW aspect.

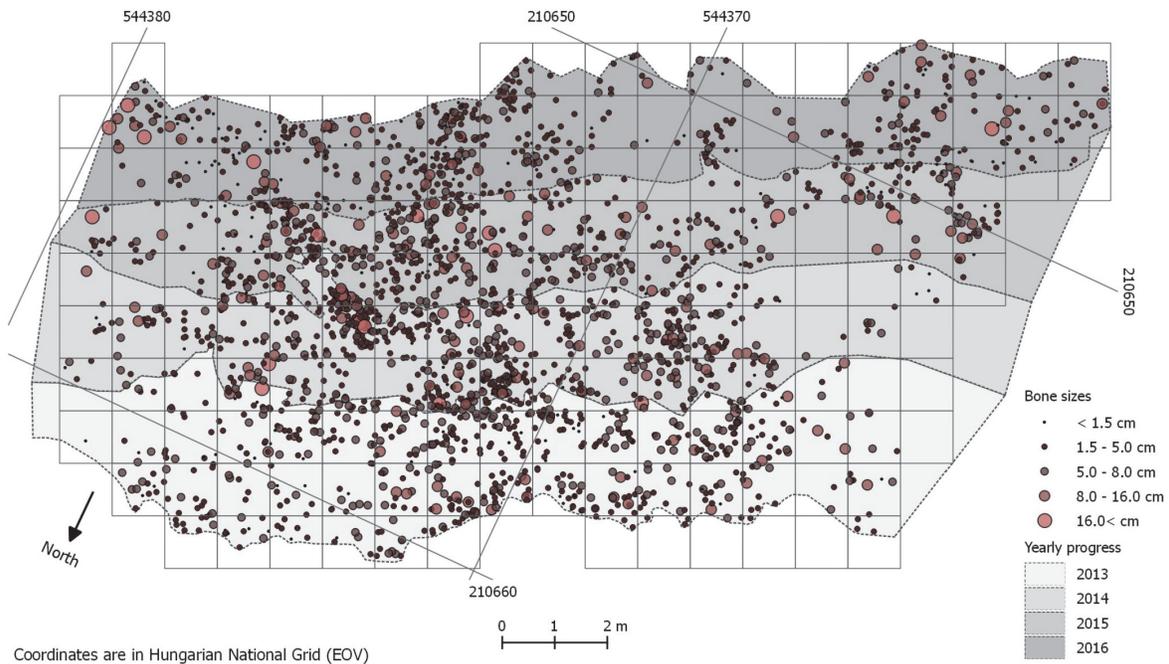


FIGURE 10. Horizontal distribution of the bones of varying sizes from the Late Cretaceous Iharkút vertebrate locality.

The Distribution of Differently Sized Bones

The investigation of the size distribution of the bone material can answer the research questions, which are focusing on the sedimentation of the bone-bearing materials, since the bones behave as discrete sedimentary particles and thus they become sorted by size, shape, and density (Aslan and Behrensmeyer, 1996; Behrensmeyer, 1975). Several empirical observations were conducted in laboratories in order to determine the dispersal potential of different bone elements (Behrensmeyer, 1975; Coard and Dennell, 1995; Dodson, 1973; Kaufmann et al., 2011; Voorhies, 1969). Their results indicate that this sorting pattern refers to transport conditions and that the size, shape, and density of bones are key factors during the transportation. The vertical and horizontal distribution of different types of bones are varying according to the physical properties of the bonebed, and thus, the variations in depositional processes are best demonstrated in three dimensions to establish the relative changes across the site (Anderson and Burke, 2008; Bamforth et al., 2005; Britt et al., 2009; Gallotti et al., 2011).

Using a standard GIS program and the original database, the horizontal size distribution can be represented as a map (Figure 10) without using the 3D modelling component program or the Excel macro, because the database of the Iharkút

bonebed contained the necessary attributes for such analysis (size and type tables – see Figure 2). However, the analysis of the vertical distribution, or creating maps of certain layers of the bonebed, requires the additional relative position data (“dist-FromBase” and “bedThickness” fields), which were generated with the spatial modelling component program (JS) and exported as new attributes of the bone material into the database (see previous chapter). The analysis of the vertical distribution can be completed using Excel (Figure 11). Due to the varying thickness of the bonebed, the relative positions were the most informative, when only the thicker (>50 cm, see Figure 5) part of the bonebed was analyzed.

Analysis of Associations among the Findings

The 3D depiction of the spatial distribution of bones can clarify whether there are potential associations among elements, especially when multiple animals are present and represented by broken and disarticulated remains (Eberth et al., 2007). The degree of articulation in a bonebed is generally estimated in a qualitative sense (e.g., partially articulated) based on individual observations, while the probability of association of isolated skeletal elements is considered zero as long as there is no evidence for the probability of association among the vertebrate remains (Badgley, 1986a). However, degree of element association in a bonebed can be

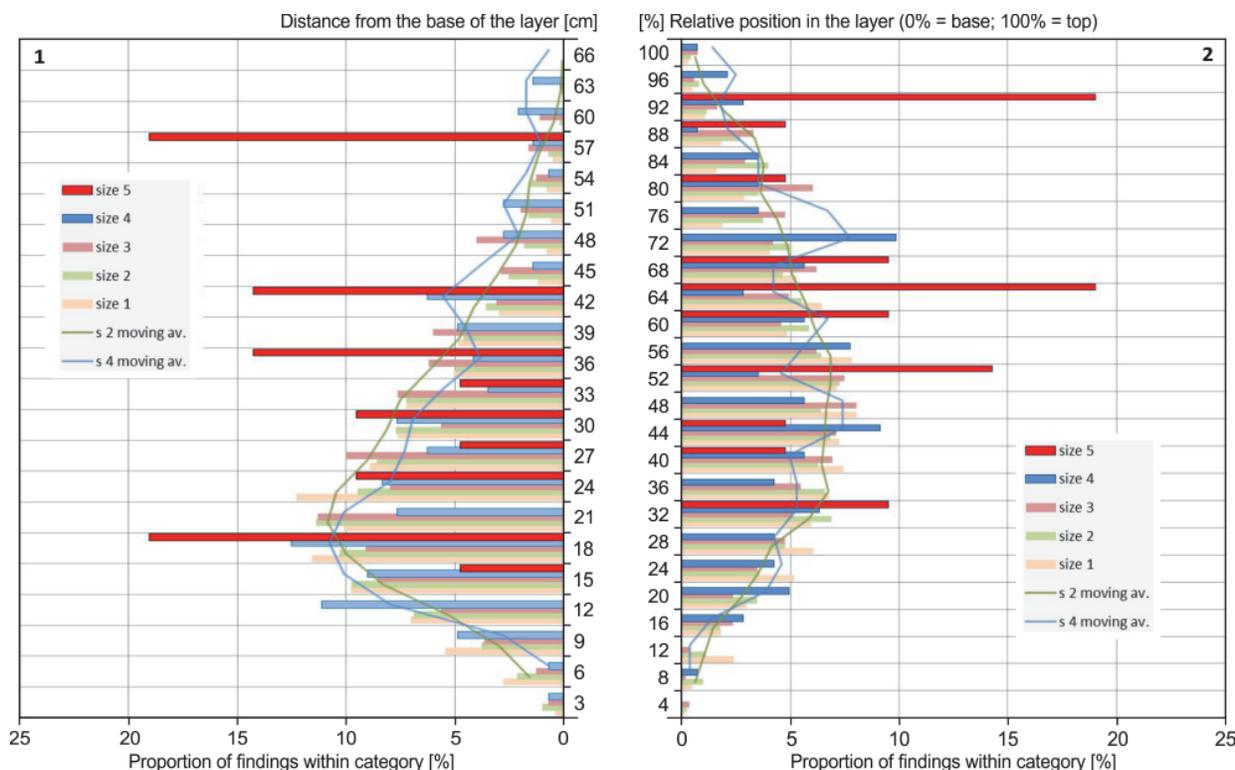


FIGURE 11. Vertical distribution of bone materials from the Late Cretaceous Iharkút vertebrate locality grouped by their sizes. On the left (1) the absolute distances are shown on the vertical axis, while on the right (2) the distances are normalized to the thickness of the bonebed.

gauged in a qualitative fashion by evaluating the spatial proximity of bones in relation to original anatomic association (Eberth et al., 2007). Such spatial analysis can be executed on a geodatabase of the findings, and the results (as maps or 3D line plots) highlight the relationships of vertebrate remains.

The association pattern depends on different factors: i) the specified taxa as the base of the search, ii) the specified taxa as the target of the search, and iii) the defined buffer distance where the targets are searched. To quantify the probability of associations, a few already connected findings can provide the control data. The links between the associated findings are ranked by their proportion to the control distances. The analysis of the association pattern can be followed by a subsequent physical examination of the concerning materials.

Measurement of probability of association of isolated skeletal elements can also help in those cases when we want to connect different undetermined elements with well-defined cranial or mandibular elements. For example, four different taxa of *Mesoeucrocodylia* are documented based on cranial elements and tooth morphology within the Iharkút vertebrate assemblage (Ósi et al., 2012;

Rabi and Sebók, 2015). However, mesoeucrocodylian postcranial elements from the same site cannot be easily assigned to any taxon, because their conservative morphology prevents the recognition of taxon-specific characters. In this case, the analysis of the association-patterns within the data can be a key tool to reveal certain connections between the cranial and postcranial elements of a single crocodyliform taxon (Figure 12).

With the changing of the search radius, a dynamic variation of line-pattern is also informative, regarding the possible location of carcasses (Figure 13). Such dynamical analysis can be performed with the iterative querying of the database using the GroupSelect macro.

CONCLUSION

The demonstrated methods are new in a sense that such a spatial analysis has not been applied in taphonomical studies yet. Our aim was to create detailed documentation of this analysis to provide a workflow model. Although, parts of the workflow are available in 2D programs for GIS purposes, the tackled taphonomical inquiries are better executed in 3D in the demonstrated way.

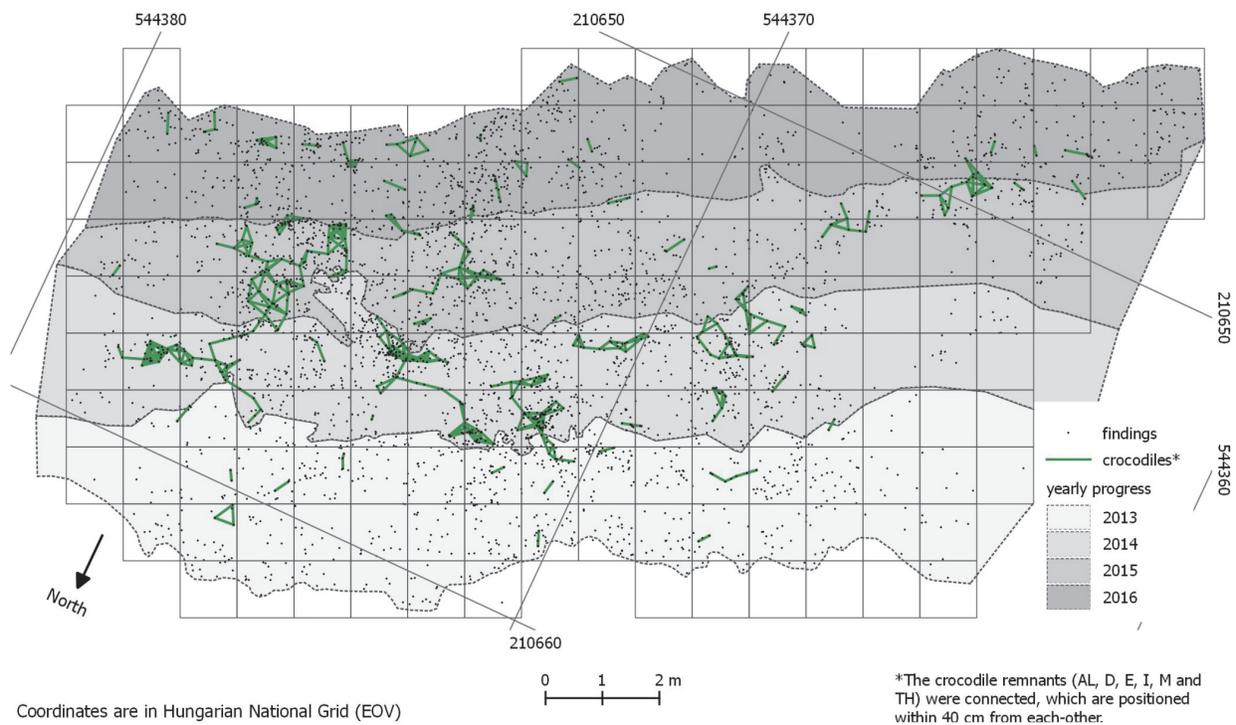


FIGURE 12. Association pattern of the crocodile fossils at the Santonian Iharkút locality (site SZ-6).

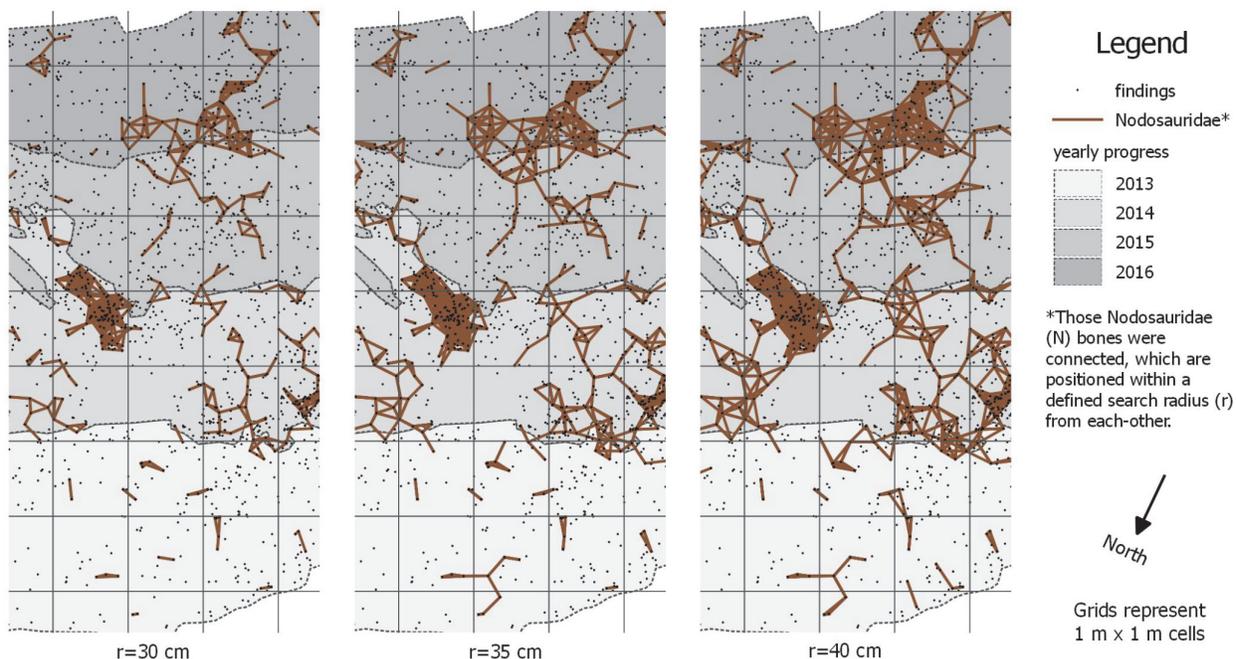


FIGURE 13. The changing pattern of the Nodosauridae bone associations amongst fossils at the Santonian Iharkút locality (site SZ-6).

Without a 3D model, the spatial analysis of the bonebed is problematic because the relative position of the findings cannot be calculated and using only the elevation is not enough. In the workflow, we defined the optimal database structure, which included the physical measuring of the fossil-bearing strata. A base- and top-layer model – based on GPS measurements – was used in Jewel Suite to calculate the relative position of each fossil. Although, the presented JS modelling program provides easily executable solution for this, it is obvious that alternative methods (e.g., other modelling programs) can provide the same results.

Also, a significant part of the workflow was designed to exclude specialized commercial programs and to be manageable for those paleontologists, who got used to storing their data in simple table format (i.e., Excel). The developed VBA macro (GroupSelect) is optimized for Excel 2010 (v. 14) and newer. It helps to run complex spatial queries and exports the results in simple text format. Even those who have no access to JS (or similar 3D programs) can benefit from the database management and interpret the results on 2D maps. In the presented utilizations, such results were visualized with the QGIS open source 2D GIS application. The emphasis of the presented methods was on the stepwise process which results in maps, distribution diagrams, and 3D models from the database.

The new technique, presented here, can be an easily applicable method accessing paleontological field work. Results of these analyses can abruptly increase taphonomical data, help in clarifying

taxonomical assignments of questionable but related fossil elements, and, in general, widen and help to visualize our interpretation in palaeoecological reconstructions.

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SUPPLEMENTARY 1.

The complete database of the paleontological findings between 2013 and 2016 at the Iharkút dinosaur locality, Hungary in Excel multi-sheet format. The Excel file contains the Visual Basic macro (GroupSelect) handling the spatial queries (available as zipped file <https://palaeo-electronica.org/content/2018/2370-mapping-the-past>).

SUPPLEMENTARY 2.

User manual for the database and the Visual Basic macro (GroupSelect) handling the spatial queries. (available as zipped file <https://palaeo-electronica.org/content/2018/2370-mapping-the-past>).