Scientific Annals, School of Geology Aristotle University of Thessaloniki (AUTH)	Special volume 98	141-146	Thessaloniki, 2006

HIGH-RESOLUTION X-RAY COMPUTED TOMOGRAPHY APPLIED TO THE STUDY OF SOME ENDOCRANIAL TRAITS IN CAVE AND BROWN BEARS

Nuria GARCÍA[1,2], Elena SANTOS[3], Juan Luis ARSUAGA[1,2] & José Miguel CARRETERO[2,3]

ABSTRACT: A complete skull of *Ursus deningeri* recovered from Sima de los Huesos (Middle Pleistocene) of Sierra de Atapuerca (Spain) (Torres, 1988; Arsuaga *et al.*, 1997; García *et al.*, 1997; García, 2003) was studied by using X-ray Computed Tomography (CT). This technique allowed the extraction of new relevant information from the endocranial structures, while avoiding any damage (Conroy & Vannier, 1984; Brochu, 2000; Ketcham & Carlson, 2001; Marino *et al.*, 2001). An undescribed endocranial cavity of *U. deningeri* was compared with related species such as *Ursus spelaeus* and *Ursus arctos*. The characters studied included the braincase morphology and also quantitative measurements which are only available with this technique. The surface of the frontal sinuses and the brain cavity, the shape of the ethmoid bone, and the basioccipital pneumatization were analyzed. The resulting analysis supports the relationship of the two ursids included in the cave bear lineage (*U. deningeri* and *U. spelaeus*), as among others, being similar in the endocranial roof or the palatine profile. Moreover, some endocranial morphologies observed in brown bears such as, thin basioccipital, elongated frontal sinuses and very rounded olfactory bulbs, differ from cave bears, and are here interpreted as plesiomorphies. New endocranial traits are described which will be very useful in the study of the ursid phylogeny.

Key words: *Ursus deningeri,* Atapuerca, CT scan, endocranium, frontal sinus, basioccipital, pneumatization.

INTRODUCTION

In the mid-1970s and 1980s new methods, such as the use of high-resolution X-ray Computed Tomography (CT), were applied for the first time in palaeontology (Jungers & Minns, 1979; Conroy & Vannier, 1984). This technique allows for the non-destructive analysis and measurement of internal structures and cavities in fossil remains (Joeckel, 1998; Brochu, 2000; Marino *et al.*, 2001). The use of CT is particularly useful for reconstructing the virtual endocast in well preserved fossil skulls (Rowe *et al.*, 1997; Brochu, 2000; Franzosa & Rowe, 2005).

The Sierra de Atapuerca is a complex system of cavities located at 14 km at the east of Burgos (Spain) (fig. 1), and represents one of the most important Pleistocene localities in Europe, due to a continuous human presence and abundant faunal record ranging from around 1.2 Ma up to the present. Several cave fillings have yielded fossils and/or artefacts, among the trench (Trinchera) deposits and also in Sima de los Huesos (SH), (fig. 2).

The Sima de los Huesos (SH) site is located deep inside the Cueva Mayor-Cueva del Silo cave system, far removed from any modern day surface entrance. The site has yielded the well-preserved skeletal remains of dozens of human individuals (Arsuaga *et al.*, 1997) lying stratigraphically below a jumble of bones of the Middle Pleis-

1 Dpto de Paleontología. Facultad de Ciencias Geológicas. Universidad Complutense de Madrid. Ciudad Universitaria s/n, 28040 Madrid (Spain). ngarcia@isciii.es, jlarsuaga@isciii.es
2 Centro Mixto UCM-ISCIII de Evolución y Comportamiento Humanos. C/ Sinesio Delgado 4, Pab. 14, 28029 Madrid (Spain).
3 Laboratorio de Evolución Humana. Dpto de Ciencias Históricas y Geografía. Edificio I+D+i. Universidad de Burgos. Plza. Misael Bañuelos s/n., 09001 Burgos (Spain), esantos@beca.ubu.es, jmcarre@ubu.es

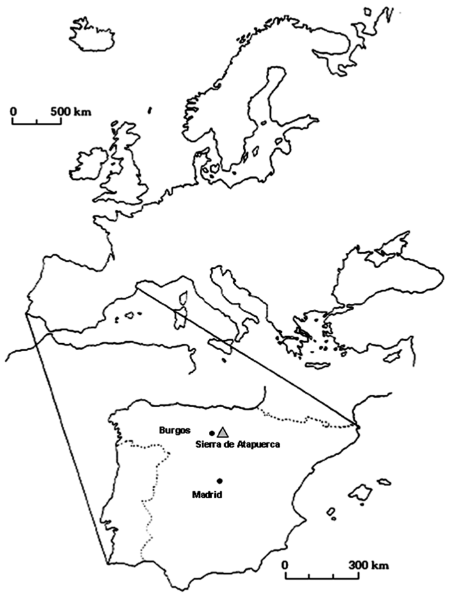

Figure 1. Sierra de Atapuerca, location.

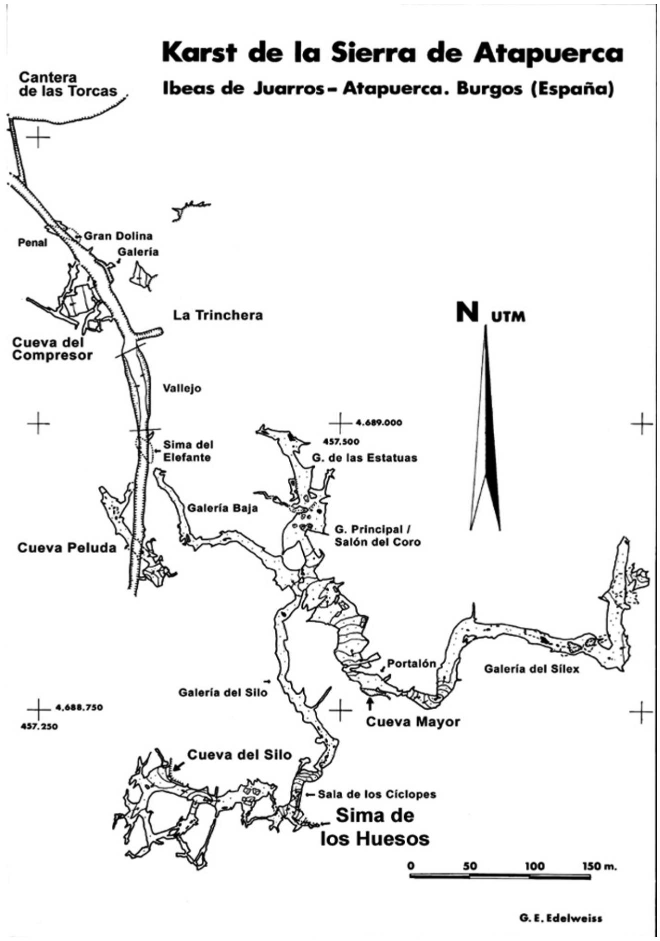

Figure 2. Plan of the Sierra de Atapuerca cave system (G.E. Edelweis).

tocene cave bear *Ursus deningeri* (García *et al.*, 1997; García, 2003). No herbivores are present among the faunal assemblage from the site, contrasting with their common occurrence at hominid occupation sites.

In the 1999 field session a nearly complete skull (SH99 T/U-13/14-68) from the Sima de los Huesos (fig. 3) was recovered in association with postcranial elements. A study of the cranial morphology of this specimen was undertaken through CT scanning and virtual reconstruction. Several endocranial traits have been analyzed and their expression across taxa has been investigated to determine their usefulness in reconstructing phylogenetic relationships within the ursid evolutionary lineage.

The *U. spelaeus* skull is characterized in classic descriptions by a strong development in the frontal area (glabella), showing a very distinctive doming of the forehead (convex forehead), which is strongly vaulted, with bulging tubera frontalis (Marinelli, 1931; Kurtén, 1968; 1972; Cordy, 1972; Torres, 1988; Mazza & Rustioni, 1994). This profile has also been observed in the *U. deningeri* skulls from Mauer, Mosbach (von Reichenau, 1904; 1906), Petralona (Kurtén & Poulianos, 1977; 1981; Tsoukala, 1989) and la Fage (Bonifay, 1975). This feature results in a characteristic step-profile in lateral view. The inner part of the frontal bone presents a large frontal sinus (FS). This character readily distinguishes both *U. deningeri and U. spelaeus* from the living brown bear *U. arctos* (Kurtén, 1968; Mazza & Rustioni, 1994).

MATERIAL AND METHODS

The *U. deningeri* cranium (SH99 T/U-13/14-68) from the Sima de los Huesos, was scanned, in the coronal axis, at the Hospital General Yagüe (Burgos, Spain), with the following parameters: scanner energy was 120 kV and 150 mA, slice thickness 0.5 mm, and inter-slice spacing was 0.5 mm. The slices were obtained in DICOM format.

For comparative purposes, two *Ursus spelaeus* (Cantabria, Spain) and seven *Ursus arctos* (north of Spain) specimens have also been scanned and virtually reconstructed (tab. 1). All specimens were scanned in the coronal axis using either a Helicoidal Asteion CT scanner at the Hos-

Table 1
Specimens scanned *= unknown origin.

Specimen	Sex	Age	Chronology	Locality
U. deningeri SH99 T/ U-13/14-68	♂	Non fully-adult	Middle Pleistocene	Atapuerca (Burgos, Spain)
U. spelaeus 1	♂	Non fully-adult	Late Pleistocene	* (Cantabria, Spain)
U. spelaeus 2	♀	Adult	Late Pleistocene	Las Monedas Cave (Puente Viesgo, Cantabria, Spain)
U. arctos 1	♀	Adult	Holocene	Maza Cotina (Burgos, Spain)
U. arctos 2	♂	Adult	Holocene	* (north of Spain)
U. arctos 3	♂	Adult	Holocene	La Machorra Cave (Burgos, Spain)
U. arctos 4	♂	Adult	Holocene	Las Motas 33 Cave (Burgos, Spain)
U. arctos 5	♂	Adult	Holocene	Las Motas 33 Cave (Burgos, Spain)
U. arctos 6	♀	Adult	Holocene	* (north of Spain)
U. arctos 7	♀	Adult	Holocene	Palencia (Spain)

pital General Yagüe (Burgos, Spain) or an YXLON MU 2000-CT scanner at the University of Burgos (Spain). The sex determination of the specimens was made using the anteroposterior diameter of the canine.

The slices were used to create three-dimensional computer models of the objects using the Mimics 8.1 (Materialise N.V.) and VGStudio MAX 1.2 (Volume Graphics GmbH) software packages. This software allows the taking of volumetric and linear measurements in both 2D and 3D. To check on the reliability of the virtual measurements, selected dimensions were also measured with standard sliding callipers, and no significant differences were found.

DESCRIPTION

The skull of a non-fully adult specimen of *Ursus deningeri* (SH99 T/U-13/14-68), from the Sima de los Huesos, presents a doming of the forehead also observed in the adult specimens of *U. deningeri* from Petralona Cave (Kurtén & Poulianos, 1977; 1981; Tsoukala, 1989), Mauer, Mosbach (von Reichenau, 1904; 1906) and la Fage (Bonifay, 1975). This feature does not occur in *U. arctos* (Bonifay, 1975; Mazza & Rustioni, 1994). The skull profile in the SH specimen is interrupted at the orbital region, like in *U. spelaeus*, dividing the facial skeleton from the braincase and giving a stepped appearance (fig. 4).

Frontal Bone and Frontal Sinuses

The frontal bones are broad and forming part of the brain cavity and the olfactory tract. The enlargement of the anterior part of the frontal bones and the vaulted forehead in the SH specimen, both typical traits of *U. spelaeus*, reveals large frontal sinuses (FS). The FS are asymmetric, divided by a variable number of bony septa and connected to the middle meatus via the frontal recess. The anterior part of the FS is anteroposteriorly elongated, and the caudal portion is more rounded (fig. 5).

The FS are dorsoventrally enlarged in the SH specimen and *U. spelaeus*, while in *U. arctos*, they are anteroposteriorly elongated. The vaulted forehead observed in the SH frontal bone is reflected in the shape of the rostral frontal sinuses (RFS) which is rounded in both the SH skull and *U. spelaeus*. This region in *U. arctos* is completely different, being much more receding.

Palatine

In sagittal view the palatine profile of the SH specimen is thick and curved. This profile in *U. spelaeus* is thicker and less arched, while in *U. arctos* is thin and practically straight. In ventral view this bone is convex in both cave bears and slightly concave in brown bears.

Basioccipital

The basioccipital bone shows clear differences between *U. speleaus*, which is very thick and pneumatized, and *U. arctos*, which is much thinner and shows no signs of pneumatization (Torres, 1988). The basioccipital in the non-fully adult specimen of *U. deningeri* from SH is thick (as in *U. spelaeus*) but is not pneumatized (as *U. arctos*) (fig. 6).

Ethmoid bone and cribriform plate

The morphology of the ethmoid bone, particularly the cribriform plate (CP), showing taxonomic variation (Torres, 1988), and it is correlated to the structure of the brain. In *U. arctos*, the CP is globular. In *U. spelaeus*, the CP is ellipsoid and strangulated. The *U. deningeri* skull,

Figure 3. *U. deningeri* skull from Sima de los Huesos (Sierra de Atapuerca).

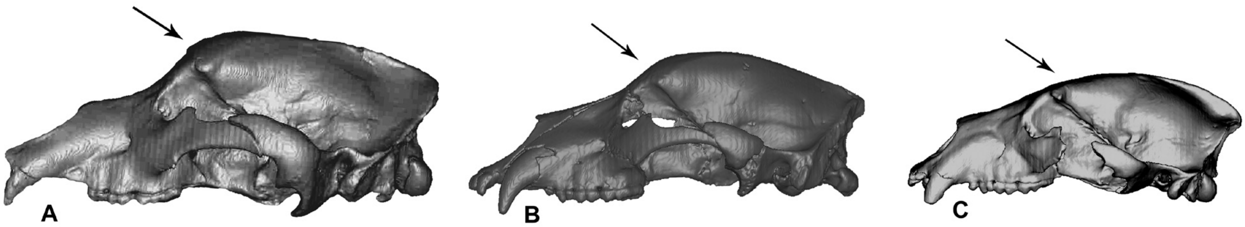

Figure 4. A. *U. spelaeus* 2, B: *U. deningeri* cranium from the Sima de los Huesos and C: *U. arctos* 1. The arrows indicate the stepped forehead in both cave bear and the absence of this trait in brown bear.

Figure 5. Digital image of the *Ursus deningeri* skull from Sima de los Huesos. Top: sagittal view. Bottom: frontal sinuses area in detail. Right: dorsal view. The images show the frontal sinuses filling the vaulted forehead.

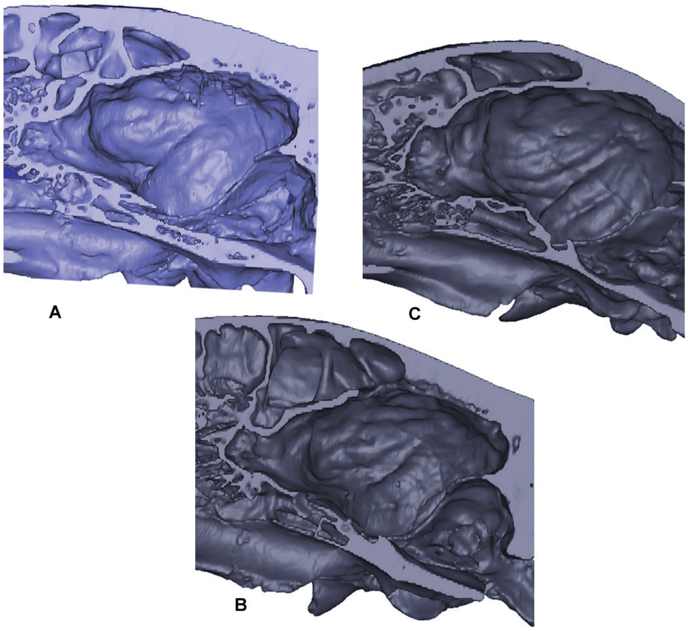

Figure 6. Parasagittal sections of skulls, in which the basioccipital bone and the profile of the brain cavity can be seen. A: *Ursus spelaeus*. B: *Ursus deningeri*. C: *Ursus arctos*.

Profile of brain cavity

In *U. arctos*, the antero-dorsal profile of the brain cavity describes a pronounced curve, while in *U. spelaeus* this contour is clearly straight (fig. 6). In the SH cranium, the antero-dorsal outline of the brain cavity is intermediate between both morphologies, although it more closely approaches the condition seen in *U. spelaeus*.

CONCLUSIONS

High resolution CT scanning of fossil specimens is a non-destructive method which allows the description of new anatomical features of the endocranium. This technique will allow future investigations on the internal cranial anatomy of ursids for a better understanding of their phylogeny and adaptations.

In this preliminary approach we were able to observe some derived traits in the *Ursus deningeri* from SH that are shared with the analyzed *U. spelaeus* specimens, and which differ from *U. arctos*:

- A stepped forehead.
- A cranial vault with a straight profile,
- A rostral endocranial fossa clearly independent from the rest of the brain cavity.
- A thick basioccipital
- A thick palatine.
- A rounded frontal sinuses.

Furthermore the SH skull shows, for a number of traits, an intermediate stage between *U. arctos* and *U. spelaeus*, but in all the cases is closer to the later species:

- Palatine more curved (than *U. spelaeus)*.
- Basioccipital not pneumatized.
- The antero-dorsal outline of the brain cavity is intermediate between both morphologies.
- The joint between the frontal and ethmoid bones are more constricted (than *U. spelaeus*).

The endocranial traits here analyzed show two different patterns of expression between the cave bear and brown bear lineages. The SH *U. deningeri* skull can be aligned within the cave bear pattern in all the traits, and support the hypothesis that *U. deningeri* represents an initial evolutionary stage within the cave bear phylogenetic lineage.

Acknowledgments: CT scanning was carried out by F. Montes and J. M. Nieto, at the Hospital General Yagüe, and L. Rodriguez helped during the CT scanning process, at the University of Burgos High-Resolution X-ray Computed Tomography Facility (Burgos, Spain). We thank our colleagues from Centro Mixto UCM-ISCIII sobre Evolución y Comportamiento Humanos and the Laboratorio de Evolución Humana at Burgos University, for their help in the field and laboratory works. We are grateful to A. I. Ortega from the Edelweiss Speleologic Group and F. Alférez from UCM for providing access to some specimens of ursids used in this study. We are very grateful to G. Withalm for his constructive comments and L. Laughlan who revised the English version. This study has been funded by the Dirección General de Investigación Científica y Técnica de España (Project nº.BOS2003-08938-C03-01) and by the Consejería de Educación de la Junta de Castilla y León (Project nº. BU032A06). E. Santos received a grant from the Fundación Siglo para las Artes of the Junta de Castilla y León (Spain).

REFERENCES

ARSUAGA, J. L., MARTINEZ, I., GRACIA, A., CARRETERO, J. M., LORENZO, C., GARCIA, N. & ORTEGA, A.I., 1997. Sima de los Huesos (Sierra de Atapuerca, Spain). The site.- *J. Hum. Evol.*, **33**: 109-127, London.

BONIFAY, M. F., 1975. Le Ursidès du gisement des Abimes de la Fage a Noailles (Corrèze) (*Ursus deningeri* VON REICHENAU).- *Nouv. Arch. Mus. Hist. nat. Lyon*, **13**: 21-28, Lyon.

BROCHU, C. A., 2000. A digitally rendered endocast of *Tyrannosaurus rex*.- *J. Vertebr. Paleontol.*, **20**: 1-6, Northbrook.

CONROY, G. C. & VANNIER, M. W., 1984. Noninvasive three-dimensional computer imaging of matrix-filled fossil skulls by high-resolution computed tomography.- *Science*, **226**: 456-458, Washington D.C.

CORDY, J. M., 1972. Étude de la variabilité des crânes d' ours des cavernes de la collection Schmerling.- *Ann. Paléon.*, **58**: 151-207, Paris.

FRANZOSA, J. & ROWE, T., 2005. Cranial endocast of the Cretaceous theropod dinosaur *Acrocanthosaurus atokensis*.- *J. Vertebr. Paleontol.*, **25**: 859-864, Northbrook.

GARCÍA, N., 2003. Revisión de los úrsidos pleistocenos en Europa: relaciones filogenéticas entre los úrsidos del último millón de años.- In: "Osos y otros carnívoros de la Sierra de Atapuerca". Fundación Oso de Asturias, pp. 414-468 Oviedo.

GARCIA, N., ARSUAGA, J. L. & TORRES, T., 1997. The carnivore remains from the Sima de los Huesos Middle Pleistocene site (Sierra de Atapuerca, Spain).- *J. Hum. Evol.,* **33**: 155-174, London.

JOECKEL, R. M., 1998. Unique frontal sinuses in fossil and living Hyaenidae (Mammalia, Carnivora): Description and Interpretation.- *J. Vertebr. Paleontol.,* **18**: 627-639, Northbrook.

JUNGERS, W. L. & MINNS, R.J ., 1979. Computed tomography and biomechanical analysis of fossil long bones.- *Am. J. Phys. Anthropol.*, **50**: 285-290, New York.

KETCHAM, R. A. & CARLSON, W. D., 2001. Acquisition, optimization and interpretation of X-ray computed tomographic imagery: applications to the geosciences.- *Computers & Geosciences*, **27**: 381-400, Ottawa.

KURTÉN, B., 1968. Pleistocene Mammals of Europe. London: WEIDENFELD AND NICHOLSON, 317 pp.

KURTÉN, B., 1972. The Ice Age. New York: G. P. PUTNAMS Sons. 179 pp.

KURTÉN, B. & POULIANOS, A. N., 1977. New Stratigraphic and faunal material from Petralona Cave, with special reference to the Carnivora.- *Anthropos*, **4**: 47-130, Athens.

KURTÉN, B. & POULIANOS, A. N., 1981. Fossil Carnivora of Petralona cave, status of 1980.- *Anthropos*, **8**: 9-56, Athens.

MARINELLI, W., 1931. Der Schädel des Höhlenbären. In: ABEL, O. & KYRLE, G. (Eds.), Die Drachenhöhle bei Mixnitz.- *Speläol. Monogr.*, **7/8**: 332-497, Wien.

MARINO, L., SUDHEIMER, K. D., MURPHY, T. L., DAVIS, K.K., PABST, A., MCLELLAN, W. A., RILLING, J. K. & JOHNSON, J. I., 2001. Anatomy and three-dimensional reconstructions of the brain of a bottlenose dolphin (*Tursiops truncatus*) from magnetic resonance images.- *Anat. Rec.*, **266**: 397-414, Utah.

MAZZA, P. & RUSTIONI, M., 1994. On the phylogeny of Eurasian bears. Palaeontographica Abteilung. A.- *Palaeontographica* ABT. A, **230**: 1-38, Stuttgart.

REICHENAU, W. v., 1904. Über eine neue fossile Bären-Art *Ursus deningeri* MIHI aus den fluviatilen Sanden von Mosbach.- *Jahrb. d. nass. Ver. f. Nat.,* **57**:1-11, 7 Tab., Wiesbaden.

REICHENAU, W. V., 1906. Beiträge zur näheren Kenntnis der Carnivoren aus den Sandenvon Mauer und Mosbach.- *Abh. Grossherzogl. Hess. geol. Landesanst. Darmstadt*, **4**: 189-313.

ROWE, T., KAPPELMAN, J., CARLSON, W. D., KETCHAM, R. A. & DENISON, C., 1997. High-Resolution Computed Tomography: a breakthrough technology for Earth scientists.- *Geotimes*, **42**: 23-27, Alexandria.

TORRES, T., 1988. Osos (Mammalia, Carnivora, Ursidae) del Pleistoceno Ibérico (*Ursus spelaeus* Ros.-Hein, *Ursus deningeri* von. Reich. y *Ursus arctos* L.). I. Filogenia, distribución estratigráfica y geográfica. Estudio anatómico y métrico del cráneo.- *Bol. Geol. y Min.*, **99**: 3-46, Madrid.

TSOUKALA, E., 1989. Contribution to the study of the Pleistocene fauna of large mammals (CARNIVORA, PERISSODACTYLA, ARTIODACTYLA) from Petralona Cave (Chalkidiki, N. Greece). PhD *Thesis*, Aristotle University of Thessaloniki, *Sci. Ann.*, School of Geology, **1(8)**: 1-360, 124 fig., 64 tabl., 62. pl., (in Greek, with summary in English).- *C.R.A.S.* Paris, 1991, **312 (II):** 331-336 (preliminary report).