**The skeleton of Amud 7, and its implication for Neandertal biology.**

Ella Been1,2,Erella Hovers3,4, Yoel Rak2, Adeline Le Cabec5, Christopher Dean6,7, Alon Barash8

1Department of Sports Therapy, Faculty of Health Professions, Ono Academic College, Kiryat Ono, 55107, Israel

2Department of Anatomy and Anthropology, Faculty of Medicine, Tel Aviv University, Tel Aviv, 69978, Israel

3Institute of Archaeology, the Hebrew University of Jerusalem, Jerusalem, 91905, Israel

4Institute of Human Origins, Arizona State University, P.O. Box 874101, Tempe, AZ, 85287-4101, Israel

5Univ. Bordeaux, CNRS, Ministère de la Culture, PACEA, UMR 5199, F-33600 Pessac, France

6Centre for Human Evolution Research, Natural History Museum, Cromwell Road, London SW7 5BD, UK

7Department of Cell and Developmental Biology, University College London, Gower Street, London WC1E 6BT, UK

8Azrieli Faculty of Medicine, Bar Ilan University, Zefat, 13115, Israel

**Key words:** Middle paleolithic; Developmental trajectories; 3D reconstruction; Phylogeny; Homo neanderthalensis.

**Key points:**

* Amud 7 is the most complete Neandertal skeleton of an infant aged 6 to 14 months. As such it fills an important gap in our knowledge of Neandertals growth.
* Amud 7 shows autapomorphic Neandertal morphology both in cranial and post-cranial skeleton, indicating that Neandertals form distinct appearance from a very young age.
* Developmentally Amud 7 exhibits fast somatic growth compared with modern human infants, which may suggest no calorie restriction at early ages.
* The fast somatic growth of Neandertal infants and toddlers suggests different developmental strategies between Neandertal and modern humans at various ages.

**Introduction**

Neandertal infants, toddlers, and children are rare findings, and only a few specimens are described in the literature. In this paper, we describe a 10-month-old Neandertal baby, Amud 7, from Amud Cave. Amud 7 can provide important information regarding early childhood growth, Neandertal ontogenetic trajectories, and significant implications to Neandertal paleobiology and phylogeny.

Amud cave, in the Upper Galilee (northern Israel), is situated on the steep western slopes of Nahal (Wadi) Amud, at an elevation of 110 m below sea level. The cave, excavated in the 1960s (Suzuki & Takai, 1970), has yielded diagnostic human skeletal remains of Middle Paleolithic age, in addition to rich lithic and faunal assemblages (Hovers, Rak & Kimbel, 1991; Madella et al., 2002; Rabinovich and Hovers 2004; Watanabe ,1970; Hovers, 2004). Initial geological age estimates of the site, based on the alleged Middle-Upper Palaeolithic transitional characteristics of the lithic assemblages (Watanabe, 1965; 1970), placed it *c.* 30 ky ago (Suzuki, 1970*a*: 94). Similarly, the skeleton of Amud 1 was assigned a transitional position between Neandertals and modern humans (Suzuki, 1970*b*), due to its ‘‘advanced’’ anatomy compare with European Neandertals and the (putative) cultural transitional context in which it was found. However, by the 1980's the Amud lithic assemblages had been re-assessed as Mousterian (Jelinek, 1981; Meignen & Bar-Yosef, 1991; Ohnuma, 1992), necessitating a chronological re-assessment of Amud 1, which by that time had been acknowledged as a Neandertal (e.g., Trinkaus, 1984; Tillier *et al.*, 1988; Hovers at al., 1995). Lithic analyses from the renewed excavations at the site (1991–1994; Hovers, 2004; Hovers, Rak & Kimbel, 1991), confirmed the Middle Palaeolithic affinities of the lithic assemblages (Goder, 1997; Hovers, 1998; Alperson-Afil, 2005: Ekshtain, 2017; Hovers, 2007; Hovers, et al, *2008*). Thermoluminescence measurements performed on burnt flints suggest age estimates ranging from 50 to 70 ky for the Middle Palaeolithic sequence (Valladas et al., 1999), corroborated by comparable results of Electron Spin Resonance and Thermal ionization spectrometry Uranium-Thorium (ESR-TIMS) dating (Rink et al. 2001). Hominin remains from both campaigns derive from the upper part of the sequence (stratigraphic sub-units B2 and B1), dated by both techniques to a time range between 56-51 ky ago. All the diagnostic remains from the new excavations including Amud 7, exhibit several derived Neandertal traits (Hovers *et al.*, 1995; Pearson et al., 2020; Rak, Kimbel & Hovers, 1994, 1996).

Amud 7 is the articulated skeleton of an infant Neandertal discovered in a small niche near the northern wall of the cave (Rak *et al.*, 1994). The specimen was found lying on its right side, directly on the bedrock. Nearly 111 skeletal pieces were found *in situ* (Rak et al., 1994; Been and Rak, 2012). The base of the skull and the mandible of Amud 7 were published shortly after its discovery (Rak et al. 1994), and the rest of the skeleton was briefly described by Been and Rak (2012) (Figure 1b – the bones). Age at death was estimated to 10 months based on modern human standards of dental development and on the degree of wear (Hovers et al., 1995). From its initial discovery the skeleton exhibited taxonomic characters that were attributed to Neandertals such as oval foramen magnum, prominent medial pterygoid tubercle, and absence of mental protuberance (Rak et al., 1994). Due to stratigraphic considerations, its location in the site, skeletal completeness, and position, Amud 7 was considered an intentional burial (Figure 1a – the burial in situ). A deer maxilla leaning against its pelvis was interpreted by the excavators as a possible offering due to taphonomic considerations (Hovers et al., 1995, 2000; Rak et al., 1994, 1996).

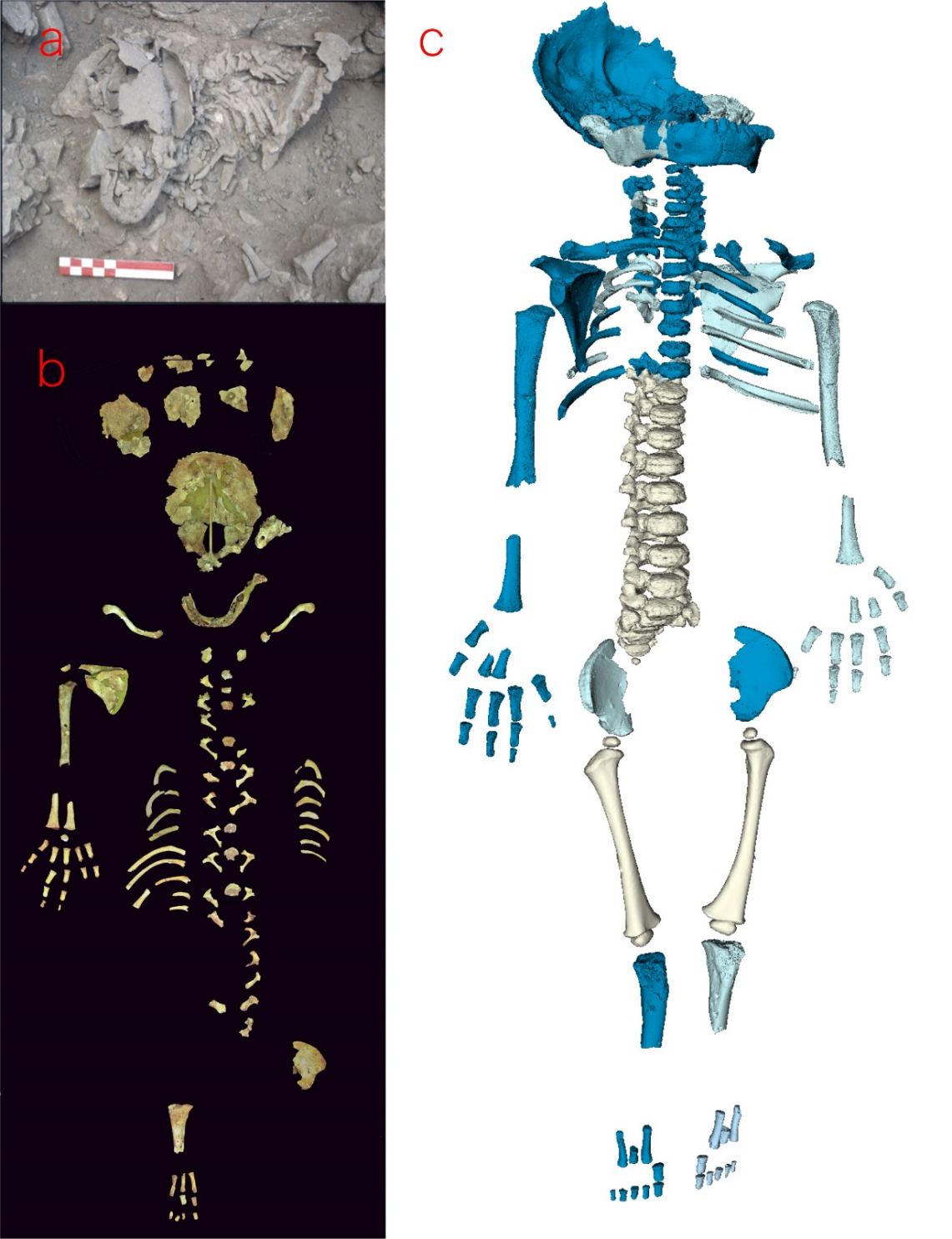
To enhance our understanding of the implication of Amud 7 to Neandertal paleobiology, the aims of this study are: first, to describe and measure the remains of Amud 7, and compare them with other young Neandertals and modern humans. Second, to 3D reconstruct the skeleton of Amud 7 including the cranial and postcranial remains to fully appreciate the entire specimen and to estimate its brain volume. Third, based on our results, to estimate age at death, height and weight of Amud 7; finally, to discuss the implications of Amud 7 to our understanding of Neandertal phylogeny, and postnatal development.

Table 1. Young Neandertal specimens with skeletal remains, listed according to age at death.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Specimen | Age | Bones  Age estimation based on | Humerus | Femur | Tibia | Spine | Cranium | Tarsal /metatarsal | Ref. |
| Le Moustier 2 | 0-0.25 m | Skeletal dev. | √ | √ | √ | √ | √ |  | Heim, 1982 |
| Mezmaiskaya | newborn 2 m | Dental eruption. | √ | √ | √ | √ | √ | √ | Golovanova et al., 1999 |
|  | 0-0.5 m | Skeletal dimensions |  |  |  |  |  |  | Ponce de Leon et al., 2008 |
| Kiik-Koba 2 | 5-7 m | Skeletal dimensions | √ | √ | √ |  |  |  | Vlcek, 1973 |
| Amud 5 | 6-9 m | Skeletal dimensions | √ |  | √ |  |  |  | Rak et al., 1994 |
| Amud 7 | 9-10 m | Dental eruption, calcification stages | √ |  | √ | √ | √ | √ | Rak et al., 1994 |
| Kebara 1 | 11-12 m | Dental eruption. | √ |  | √ | √ | √ |  | Tillier et al., 2003 |
| Shanidar 9 | Infant |  |  |  |  | √ |  |  | Trinkaus, 1983 |
| Shanidar 10 | 12-24 m | Skeletal dimensions |  |  | √ |  |  |  | Cowgill et al., 2007 |
| Dederiyeh 1 | 18-24 m | Dental eruption. | √ | √ | √ | √ | √ | √ | Dodo et al., 1998; Fukase et al., 2015; Gomez Olivencia et al 2015 |
| Dederiyeh 2 | 18-30 m | Dental eruption and skeletal dimensions |  | √ | √ | √ | √ | √ | Fukase et al., 2015;  Ponce de Leon et al., 2008; Akazawa et al., 1999 |
| Pech de l’Azé 1 | 26 -30m |  |  |  |  |  | √ |  | Faerman et al 1994 |
| La Ferrassie 8 | 22-26 m |  |  |  |  | √ | √ |  | Heim, 1982 |
| Roc de Marsal 1 | 30-42 m | Dental eruption | √ | √ | √ | √ | √ |  | Minugh-Purvis, 1988 |
| La Ferrassie 6 | 36 m | Skeletal dimensions | √ | √ | √ | √ |  | √ | Heim, 1982 |
| Shubalyuk 2 | 36m |  |  |  |  |  | √ | √ | Pap et al., 1995 |
| Cova Negra | 60 m | Skeletal dev. |  | √ |  |  | √ | √ | Arsuaga et al., 2007 |
| Engis 2 | 3 y | Dental histology |  |  |  |  | √ |  | Smith et al., 2010 |
| Gibraltar 2 (Devils tower) | 4.6 y | Dental histology |  |  |  |  | √ |  | Smith et al., 2010 |
| Krapina 1 | 7 y |  |  |  |  |  | √ |  | Minugh‐Purvis et al., 2000 |
| El Sidron | 7.7 y | Dental histology | √ | √ |  | √ | √ | √ | Rosas et al., 2017 |
| La Quina 18 | 7.75 y |  |  |  |  |  | √ |  | Ponce de Leon et al., 2008 |
| Le Fate 1 | 8-10 y |  |  |  |  |  | √ |  | Giacobini et al., 1984 |
| Teshik Tash | 10 y |  |  |  |  |  | √ |  | Weidenreich 1945 |
| Le Moustier 1 | 11.6-12.1 y | Dental histology | √ | √ | √ |  | √ |  | Daumas et al., 2021; Smith et al., 2007 |

Abbreviations: m=month, y=year

**Figure 1:** Amud 7 skeleton. a – in situ; b – layout of the skeletal remains; c – 3D reconstruction, blue – original bones, light blue – duplicated and mirrored elements, gray – 9-month-old modern human baby.

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**Results**

Post-Cranial Remains:

The post-cranial remains of Amud 7 consist of upper limb and lower limb bones, as well as the axial skeleton (Supplementary 1).

The upper limb bones comprise the right and left clavicles, right scapula, humerus, radius, ulna, metacarpal, and phalanx. These bones exhibit notable robustness in comparison to modern human infants, and their size is overall equivalent to that of a 12-14-month-old modern human infant. Despite their young age, these bones already display distinctive Neandertal features, including a robust and highly curved clavicle, a relatively narrow glenoid cavity facing more inferiorly, a superior orientation of the spine of the scapula, smaller torsion of the humeral body, and a very wide (mediolateral) distal radius (Table 2). Developmentally, there is no ossification of the epiphysis to the diaphysis of the long bones (humerus, radius, ulna).

The vertebral spine comprises a nearly complete cervical spine and representatives of the thoracic, lumbar, and sacral vertebrae (supplementary 1). The level of ossification is at stage one, indicating unfused posterior synchondrosis and neurocentral synchondrosis (Rosas et al., 2017).

The lower limb remains include a fragment of the left ilium, the proximal half of the tibia, three metatarsal bones, and six phalanges. The size of the ilium matches that of a 12-14-month-old modern human infant. The estimated length of the tibia (92 cm( is notably short compared to a 12-month-old modern human infant (Supplementary 1) and is more in line with the dimensions of a 4-6-month-old modern human infant. This might be expected given the relatively short tibia described in Neandertals (Walker et al 2011). Similar to the upper limb, these bones also display distinctive Neandertal features, such as the presence of a supra-acetabular fossa on the ilium, a robust tibia, and rounded lateral and medial borders of the tibia, in contrast to the sharp edge observed in *H. sapiens* tibia (Been et al., 2017).

Cranial remains:

Cranial elements are represented by: an occipital bone, a right petrous bone, fragments of parietal bone, an almost complete mandible, and four isolated maxillary teeth. Most of these elements were described by Rak et al. (1994).

The occipital bone is fully ossified, although a clear fusion line is still apparent between the basilar, lateral and supraoccipital parts. It displays a variety of features indicating that even at such young age, Amud 7 is clearly a Neandertal: an elongated anterior-posterior foramen magnum, an autapomorphic feature of Neandertal infants (Rak et al., 1994) as well as a clear suprainiac fossa (Hublin, 1978; Balzeau and Rougier, 2010).

Within the left petrous bone, a well-preserved left incus bone was found (Quam & Rak, 2008), which exhibits a Neandertal morphology, including a distinctive crural and intercrural shape, and large articular facet (Stoessel et al., 2016).

The mandible lacks the right ramus, and on the left side, the junction between the ramus and the corpus has undergone some restoration (Supplementary 1, figure xxx). The mental foramen is directly below the mesial portion of the deciduous first molar, as already observed by Williams and Grovitz (2004). A prominent medial pterygoid tubercle is present at the left angle of the mandible (Supplementary 1, figure xxx). The left portion of the mandibular symphysis is damaged and was restored. Yet the right side of the symphysis is well preserved; it lacks a marked mental protuberance and is pillar-shaped in sagittal section (Supplementary 1, figure xxx), as in older Neanderthals (e.g., Le Cabec et al., 2012; See supplementary 1. For a detailed description of the mandible and teeth).

Many Neanderthal-like features are present in the mandible (Rak, et al., 1994). These include a marked medial pterygoid tubercule, and mandibular condyle with distinct pterygoid fossa (Figure 2). The lack of chin, by itself, is not a Neandertal autapomorphic feature. However, given the chronological placement of this specimen, two likely candidates were present in the Levant- *H. neanderthalensis* and *H. sapiens* (Bailey and Tyron, 2023 and references therein; Been et al., 2017; Bar-Yosef et al. 1992 and references therein). The latter is the only known hominin to possess a marked chin (but see Hublin et al., 2017 for a different view).

Several bones of a person's upper jaw

Description automatically generated

Figure 2. 3D models of the Amud 7 mandible, showing the pillar-shaped profile of the mandibular symphysis, thus lacking a mental protuberance as seen in modern humans. Note the location of the mental foramina right below the mesial portion of the deciduous first molars. The restoration material is shown in light purple and turquoise.

**Table 2.** Morphological affinities of Amud 7 in comparison with *H. sapiens* and Neandertals.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Structure** | **Amud 7** | ***H. sapiens* infant** | ***H. sapiens* adult** | **Neandertal infant** | **Neandertal adult** | **Reference** |
| Suprainiac fossa | Suprainiac fossa | Not found | Not found | Suprainiac fossa | Suprainiac fossa | CS; Balzeau & Rougier (2010). |
| Foramen magnum morphology | Oval | Round - oval | Round - oval | Oval | Oval | Rak et al., 1994. |
| Incus morphology | Short intercrural distance | Long intercrural distance | Long intercrural distance | Short intercrural distance | Short intercrural distance | Stoessel et al., 2016. |
| mental protuberance (chin) | Lacking | Exist | Exist | Lacking | Lacking | Rak et al., 1994. |
| Medial pterygoid tubercle | Prominent | Flat | Flat | Prominent | Prominent | Rak et al., 1994. |
| Clavicle  robustness | Robust | Slender | Slender -robust | Robust | Robust | CS  Kondo & Dodo, 2002; Vincenzo et al., 2012. |
| Clavicle  Anteroposterior curvature | Strong | Weak | Weak | Strong | Strong -weak | CS; Kondo & Dodo, 2002; Voisin, 2006 |
| Scapula, axilloglenoid angle | 156° | 145° | 133° | 154° -170° | 141° ± 5 | CS; Kondo & Dodo, 2002; Vincenzo et al., 2012. |
| Scapula, glenoid shape | Narrow | More rounded | More rounded | Narrow - rounded | Narrow | CS; Kondo & Dodo, 2002; Vincenzo et al., 2012. |
| Orientation of the Spine of scapula | Superior dorsal | Dorsal | Dorsal |  | Superior dorsal | CS; Trinkaus, 1983. |
| Crista dorsoaxillary (sulcus marginalis) | Not developed | Not developed | Not developed | Not developed | Developed | CS; Trinkaus (1977). |
| Humeral torsion angle (around bone long axis) | Low torsion angle | High torsion angle | High torsion angle |  | Low torsion angle | CS; Carretero & Arsuaga, 1997. |
| First rib, curvature | Straight shaft | Curved shaft | Curved shaft | Straight / Curved shaft | Straight / Curved shaft | CS; Franciscus and Churchil, 2001. |
| Thickness of the iliac (cristal) tubercle | Thick | Slender | Slender | Thick | Thick | CS;  Kondo and Dodo, 2002;  Vincenzo et al., 2012. |
| Supra acetabular fossa | Deep | Shallow | Shallow | Deep | Deep | CS,  Kondo and Dodo, 2002 |
| Tibia, border morphology | Rounded - sharp | Sharp | Sharp | Rounded | Rounded | CS,  Been et al., 2017 |

CS, current study.

**Age estimation**

Age estimation for Amud 7 varies depending on the method used (SI2; SI4). The youngest estimated age is based on the histology of enamel formation of the upper right dm1, ranging from 165 to 173 days, or 5.5 to 5.75 months (equivalent to 0.45 to 0.47 years of age); See Supplementary 2 for Methods, Results and Discussion. The endocranial volume of Amud 7 (753cc) correlates with that of modern human infants aged 6-8 months. Additionally, the eruption of the two central lower incisors suggests an age estimation of 9–10 months (as reported by Rak et al., 1994), but Leighton (1968), for example, shows that both upper and lower central deciduous incisors in modern humans may emerge any time between 3 months and 12 months of age. The estimated length of the tibia (92 cm) which is notably shorter compared to a 12-month-old modern human infant (Supplementary 1), is more in line with the dimensions of a 4-6-month-old modern human infant.

A slightly older age estimation is based on the upper limb long bones. The length of the clavicle, humerus, radius, and ulna is similar to that of a 12-14-month-old modern human infant, as is the age estimation derived from the occipital pars basilaris measurements.

The relatively small endocranial volume of Amud 7 (Figure 3, Table 3) is equivalent to a 6-8 month-old modern human baby, which is lower than expected for Neandertals of this age but aligns well with the dental histological age estimate. This could result from the fact that our reconstruction is based on the constraints of the Amud 7 cranial base and mandible, which leads to an underestimation of its endocranial volume, as we do not posses the superior parts of the cranial vault. It might also reflect the variability in brain size in Neandertals, where Amud 7 is at the lower end of endocranial volume, or it might even imply some developmental or pathological condition that resulted in a relatively small endocranial volume for Amud 7.

The discrepancy in age estimation between these different methods suggests potential differences in patterns of tooth and skeletal development between Neandertals and *H. sapiens*.

**Height and weight estimation:**

The estimated height for Amud 7 based on long bones ranges from 70.3 cm to 78.6 cm (SI4). It corresponds to 7.5-month-old to 14-month-old modern human boys (WHO, 2009), with an estimated weight of 8.0-10.2 kg; or to a 9.2-month-old to 16-month-old modern human girls (WHO, 2009), with an estimated weight of 8.2-9.8 kg.

**Discussion**

Amud 7 is the most complete Neandertal specimen assigned to the age range of 6-14 months. As such it plays a major role to our understanding of Neandertal paleobiology. The skeleton bears distinct Neandertal affinities both in the cranial and postcranial remains, and its set of morphological features sheds light on the phylogeny, growth and development of Neandertals. This specimen helps to establish a morphological, taxonomic and developmental continuum of Neandertals from neonates (Le Moustier 2, Mezmaiskaya), toddlers (Dederiyah 1 and 2, Roc de Marsal), and children (El Sidron, Le Moustier 1) (Table 1).

Neandertals have been studied for over 150 years. Their morphology (Howels and le gross Clarck , swayer Tattersal) and the fact that they are probably our closest extinct relatives contribute to the ongoing debate about the taxonomical and biological relationship between Neandertals and modern humans. Some studies argue that Neandertals are a unique, highly derived species (white, rak , tattersal), while others conclude that Neanderthals and modern humans should be lumped together under the same species (WOOLPOFF).

Phylogenetically, the presence of a morphological feature at a very young age suggests that it is a taxonomical character not attributed to developmental plasticity (Garcia Martinez et al., 2020). Amud 7 exhibits Neandertal-like characteristics throughout its skeleton. Its oval foramen magnum, large medial pterygoid tubercle, robust clavicle, relatively straight first rib, unique scapular shape, thick iliac tubercle, deep supra-acetabular fossa and rounded borders of the tibia (Table 2) are part of the significant morphological differences between Neandertals and *H. sapiens* (Rak 1994; *Weaver 2009*, Trinkaus 2006*,* Garcia-Martinez *2020,* Been et al., 2017). The distinct morphology of Amud 7 indicates that Neandertals' unique morphology appears at a very young age. The magnitude of the upheaval in the anatomy of the Neandertal infant renders this taxon dramatically different from that of other hominins. This claim is in complete agreement with Le Gros Clark’s recognition of *H. neanderthalensis* based on the radically different ontogeny that Neandertals exhibit (1955). Indeed, the unusual Neandertal ontogeny is but a way of executing the highly specialized adult morphology.

Genetic evidence suggests that Neandertals and *H. sapiens* lineages began diverging about 600 ka ago, evolving largely separately in Eurasia and Africa after that time (Meyer et al., 2016; *Stringer and Crete, 2022)*. However, the genetic evidence also shows occasions of interbreeding between *H. sapiens* and Neandertals over a long period of time during the Middle Paleolithic (ca. 270-50 ky for the levant) (*Fu et al., 2015; Stringer and Crete, 2022: Haijdinjek et al., 2021*). While the nature and the extent of these interbreeding events is still debated, there is no doubt that such gene flow suggests a genetically compatible populations, perhaps accumulating to the understating that *H. neanderthalensis* and *H. sapiens* should be considered the same biological species (Green et al., 2010: Bergstrom et al., 2021).

The discrepancy between the morphological evidence and the genetic evidence is puzzling. The presence of Neandertal-like features in very young individuals most likely indicates that these unique morphologies are genetically based rather than the consequences of effects of the environment, or specific type of activity. Several explanations for this discrepancy were suggested: some researchers argued for a high diversity of hominin morphology during the middle Pleistocene (Bermúdez de Castro et al., 2019; Rosas et al., 2019). While it explains the variability in morphology, this claim does not provide a sufficient answer to the question – how or why Neandertals retained their distinctive morphology. Stringer (2012) noted that if a high diversity of hominin morphology were the case, then the Neandertal-human clade would have a morphological range far greater than what is found in humans and non-human primates today. Other scholars suggested that hybridization among newly evolved species is a common phenomenon. Mallet (2005) calculated that about 10% of newly evolved animal species are involved in hybridization (Meneganzin and Bernardi, 2023). By itself this notion also fails to explain how and why Neandertals retained their distinct morphology. According to recent studies gene flow in the late Pleistocene, during the later stages of the Middle Paleolithic, was unidirectional from Neandertals to *H. Sapiens* (Hajdinjak et al., 2018; Reilly et al 2022; but see Kuhlwilm et al., 2016; Meneganzin and Bernardi, 2023). Unidirectional gene flow, which might result from differential genetic tolerance, social rejection or high demographic fragmentation ((Lalueza-Fox, 2021), can provide an explanation as to how Neandertals retained their distinctive morphology despite interbreeding with *H. Sapiens*. Finally, while most researchers today adhere to the notion of admixture events among Middle Pleistocene *Homo* populations, this claim is still challenged (Rodrigues et al., 2018; Tournebize and Chikhi, 2023). Tournebize and Chikhi (2023) conclude that the use of genetic data to identify and quantify evolutionary events such as admixture is not simple and is heavily based on model assumptions (Finlayson et al., 2023).

Growth and developmental trajectories of Neandertals are a subject of long dispute. For many years researchers believed that Neandertals must have grown more rapidly than modern humans as both young and adult Neandertals have robust limb bones compared with modern humans, and faster dental maturation (Dean et al., 1986; Stringer and Gamble, 1993; Smith et al., 2010). Based on brain development, Hublin et al. (2015) argued that Neandertals can be distinguished from modern humans in terms of growth pattern and brain development and might have entered reproductive life earlier than *H. sapiens*. Thompson and Nelson (2000) challenged similar notions and showed that the growth trajectory of Neandertal long bones is consistent with slow linear growth compared with their dental development. They argued that this indicates that Neandertals experienced either slower or delayed linear growth or advanced dental development relative to modern humans.

Based on the current work (Table 3, Figure 2) we identified three growth stages in young Neandertals. **In newborns** –enamel formation, tooth eruption, and long bones length adhere to the same age, while endocranial volume is significantly higher compared to *H. sapiens*. **In infants/toddlers** – there is rapid somatic growth and tooth eruption while maintaining high endocranial volume compared to the enamel formation. **In children** - the somatic growth and tooth eruption evens out with enamel formation indicating a slowing down of somatic growth while maintaining high endocranial volume. Amud 7 seems to agree with this growth pattern as its somatic age estimation of 12-14 months (according to modern human standards), is clearly older than its enamel age estimation of nearly 6 months. While some researchers argued that the somatic growth of Neandertals was similar to *H. sapiens* or slower (Rosas et al., 2017; Thompson & Nelson, 2000; Martín-González et al., 2012; Mateos et al., 2014), the results of the current study indicate that the growth trajectory of young Neandertal infants is different from *H. sapiens*. They show rapid somatic growth in the first years of life that appears to even out during later childhood, excluding brain volume. This growth pattern might indicate that Neandertal infants-toddlers did not experience caloric restriction and were able to achieve fast somatic and brain development in the early years of life. This finding aligns with Ramirez Rozzi and Bermudez de Castro's (2004) McGrath et al., (2021), and Mahoney et al., (2021) who showed that Neandertals, as a *Homo* species, adapted to specific environmental conditions. They were capable of sustaining fast somatic growth while also developing and maintaining a large brain, particularly in environments with available high-calorie diets.

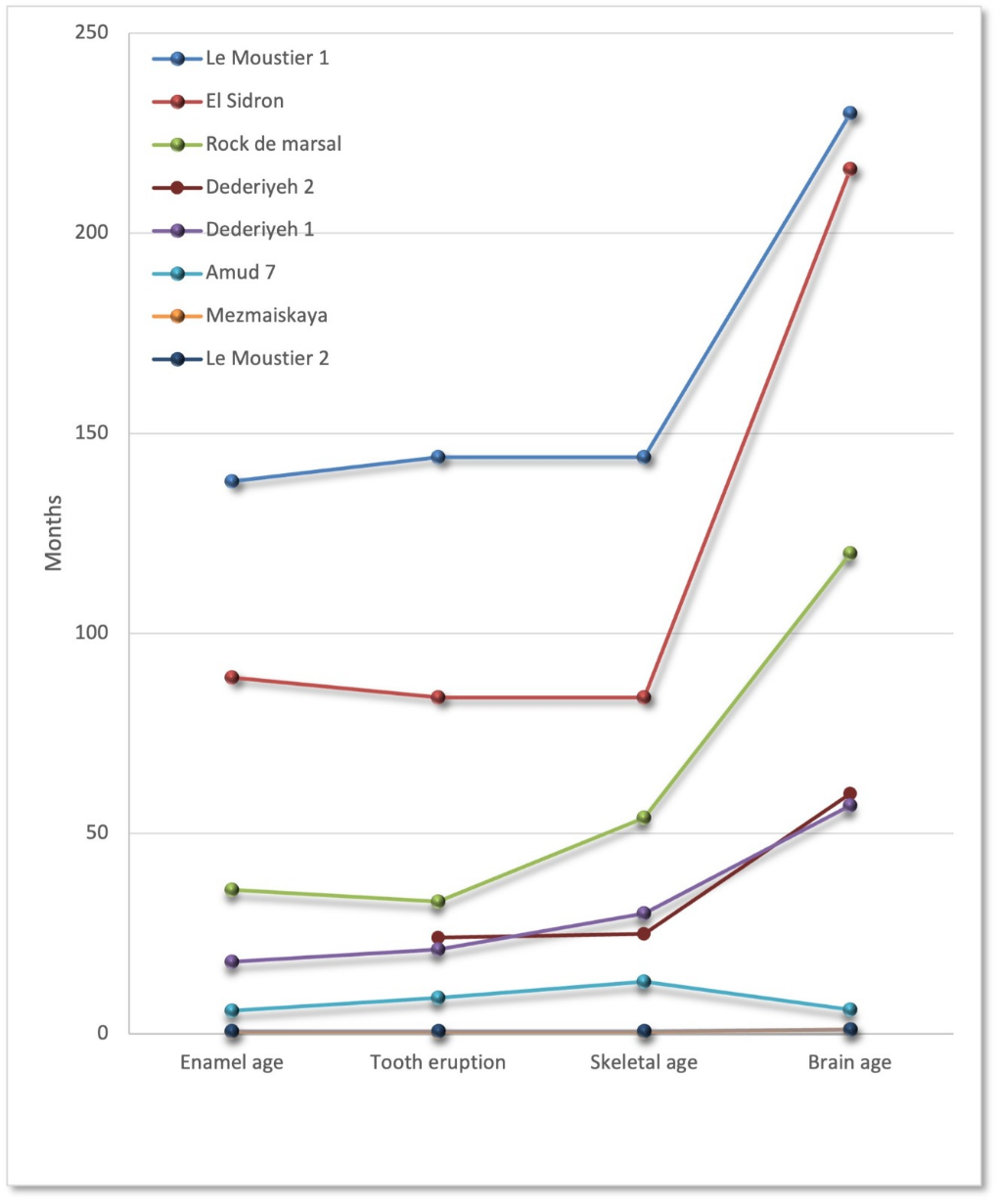
**Concluding remarks**

Neandertals are the closest and most recent relatives of *H. sapiens*. While they have been studied for well over 150 years, much of their paleobiology remains a mystery. The skeleton of Amud 7 infant provides us with a glimpse into Neanderthal’s paleobiology. This genetically close evolutionary relative, with its distinct morphology, and unique growth trajectories, suggests that different species solved their evolutionary challenges through various solutions. Thus, the morphology of Amud 7 highlights the distinctiveness of Neandertal, and their unique growth pattern that appears to differ from modern humans in different ways at different ages.

**Table 3.** Age estimation for young Neandertals based on dental histology, tooth eruption, long bones, and brain volume. Age is shown in months.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Specimen | Dental age: histology of enamel formation | Dental age: tooth eruption | Skeletal age | Brain volume age | References |
| Mezmaiskaya | 0.5 | 0.5 | 0.5 | 1 | Gunz 2012, ponce de leon 2008, weaver 2016, |
| Le Moustier 2 | 0.5 | 0.5 | 0.5 | 1 | Gunz 2011 |
| Amud 7 | 5.8 | 9 | 13 | 6 | CS, Rak et al 1994 |
| Dederiyeh 1 | 18.5 | 21 | 30 | 57 | CS, Akazawa 2002, Sasaki 2002 )in akazawa), |
| Dederiyeh 2 |  | 24 | 25 | 57 | CS, Dodo et al |
| Pech de l'Azé 1 |  | 30 |  | 72 | Faerman et al 1994; Coqueugniot and Hublin, 2007 |
| Engis 2 | 36 | 48-60 |  | 216 | Tillier, 1983;  Smith et al., 2010; Coqueugniot and Hublin, 2007 |
| Roc de Marsal | 36 | 33 - 36 | 54 | 120 | Bayle et al., 2009; Coqueugniot and Hublin, 2007 |
| Subalyuk 2 |  | 36 - 42 |  | 72 | Pap et al., 1995 |
| Gibraltar 2 (Devil’s tower) | 54 | 60 |  | 216 | Smith et al., 2010 |
| La Quina 18 |  |  |  | 84 | Ponce de Leon et al., 2008 |
| El Sidron | 89 | 84 | 84 | 216 | Rosas et al., 2017 |
| Teshik-Tash |  | 96 - 120 |  | 216 | Coqueugniot and Hublin, 2007 |
| Le Moustier 1 | 132-144 | 180-196 | 132-144 | 216 | Duamas et al., 2021, Smith et al., 2010. |

Figure 3: different developmental estimations of young Neandertals based on histology of enamel formation, tooth eruption, skeletal age, and brain volume age, based on modern human growth curves. Notice the large brain volume for all the Neandertal specimens, besides Amud 7, and the relatively more mature skeletal age of Roc de Marsal, Dederiyeh 1, and Amud 7 compared with histology of enamel formation. Also note that Le Moustier 2 and Mezmaiskaya are nearly the same age and their lines overlap.



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**Methods**

To fully understand the nature of the Amud 7 specimen we have used several methods. We started with inspection, identification, and description of the skeletal remains. This was followed by linear and angular measurements of the remains. In order to build a 3D reconstruction of the specimen we have used uCT scans of the remains. Comparisons with recent and early *H. sapiens* and with other Neandertal specimens were performed based on literature and our own measurements. For height, weight, and age estimation we have used several different methods.

**Bone identification and description**: the initial excavation and identification was conducted by Y.R. upon discovery. At a later stage (2010 – 2012) axial skeleton remains (i.e. vertebrae and ribs) were further identified and described (E.B.) (Rak et al., 1994; Been and Rak, 2012). A detailed description of the remains can be found in supplementary 2.

**Linear and angular measurements:** linear measurements of the postcranial remains were performed using a digital Mitutoyo caliper (precision of 0.01 mm). Angular measurements were performed using a goniometer. Indices were calculated based on literature (Brauer, 1988).

**3D reconstruction (Figure 1c):**

Micro-CT scans of the Amud 7 cranial and post-cranial elements were acquired by the Department of Human Evolution (Max-Plank Institute for Evolutionary Anthropology, Leipzig, Germany), in 2011. The skeletal elements were scanned on a BIR ARCTIS 225/300 industrial micro-CT scanner.

The process of the 3D reconstruction for the skeletal parts consisted of three stages: First, re-identification of all virtual scanned osteological parts and comparing them to the original bones; second, placing and aligning the virtual bones to their anatomical position; Third, duplicating missing elements from their contralateral side. This includes complete bones, such as ribs and long bones, or parts of bones such as the mandible and petrous bone.

Endocranial volume was calculated based on a warped 10-months human virtual endocranium, fitted to Amud 7 occipital and petrous bones and mandibular projection following Neubauer et al 2004. The estimated endocranial volume of Amud 7, based on the cranial reconstruction, is 753cc.

**Age estimation:** for age estimation we have used several methods. These include tooth eruption, tooth histology, long bone length,and cranial measurements.

*Tooth eruption*: Amud 7 exhibits the eruption of the two central lower incisors (Rak et al., 1994; Hovers et al., 1995).

*Tooth histology*: Here we estimate an age at death based on the histology of the pre- and postnatal enamel formation and on a very small amount of root dentine preserved in the upper right dm1 that formed immediately beforeename death. The upper right dm1 was embedded in epoxy resin and sectioned through the mesial cusps following the protocol described in Dean and Cole (2013). The neonatal line (NNL) was first identified in the enamel. Then the pre- and postnatal enamel formation times were estimated based on daily cross striations preserved within the enamel. For further details see supplementary 2.

*Long bones length*: Linear measurements of the long bones of Amud 7 were compared to that of modern humans infants and children based on literature and measurements performed in the current study (Ghantus, 1951; Maresh 1970; Kondo and Dodo 2002; Saunders et al 1993; Scheafer et al 2009)(Supplementary 1).

*Cranial measurements*:

The estimated volume was compared to endocranial volume of a sample of young modern humans (Herdon Coqueugniot & Hublin, 2012; Cofran & De Silva, 2015; Vannucci & Vannucci 2018).

*Pars basilaris of occipital bones*. The length and width of the occipital pars basilaris was measured following Scheuer and Maclaughlin-Black (1994), and compared to the results of their study.

**Height and weight estimation**

Height estimation is based on formulae by Telkka¨ *et al.*, 1962, as published by Kondo et al. (2000). Weight estimation is based on CDC growth charts for modern human boys and girls.