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MARINE VERTEBRATES FROM PLIOCENE SHELL BEDS FROM TUSCANY (ITALY): PROSPECTING, TAPHONOMY, PALAEOECOLOGY AND SYSTEMATIC PALAEONTOLOGY

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Abstract

Marine vertebrates from early Pliocene shell-beds have been studied in two areas located in southern Tuscany (Italy). In particular these shell-beds observed in four sedimentary successions outcropping in Arcille and Montalcino localities, occur at the transition between sandstones and mudstones. Marine vertebrates were found in correspondence of these laterally continuous shell-beds: three nearly complete *Metaxytherium subapenninum* specimens occur in Arcille succession, whereas a nearly complete skeleton of a Mysticete, an incomplete *Metaxytherium* cf. *subapenninum* humerus and some partially articulated Odontocete vertebrae have been found in the successions outcropping in Montalcino area. These skeletal remains are also associated to a rich fauna of invertebrate and vertebrate remains: the invertebrates are essentially represented by a diversified mollusc fauna, fragments of echinoid tests and spines and corals; the vertebrates are dominated by a rich concentration of osteichthyes and selachian teeth and bones. The sedimentary successions show a transgressive trend that starts with the deposition of yellowish coarse-grained sandstones (typical of high-energy shallow marine settings) and culminates with the massive greyish mudstones deposition that took place in an offshore environment. The laterally continuous shell-bonebeds occur within massive, fine- to very fine-grained, burrowed muddy sandstones and the stratigraphic interval including the shell-beds with marine vertebrates is considered to mark a period of sediment starvation.

The taphonomic and sedimentological features observed in this study provide a straightforward evidence for condensations of shell-bonebeds deposits: furthermore these features allow to assume a stratigraphical correlation between the shell-beds observed in Arcille area with those observed in Montalcino area. This hypothesis is also supported by micropalaeontological analyses because in two studied successions (Arcille and

Camigliano) the planktonic foraminiferal assemblages allow to attribute the vertebrate specimens to the lower part of the Zanclean (MPl2 zone) dated between 5.08 and 4.52 Ma

A systematic study on four *M. subapenninum* specimens found in Arcille area have been carried out. *Metaxytherium subapenninum* was a halitheriine dugongid distributed along the northwestern coasts of the Mediterranean Basin during the early and late Pliocene. It became extinct in the upper part of the Pliocene because of the progressive climatic cooling occurred after 3.1 Ma.

The *Metaxytherium* specimens object of this study have been described and compared with other *M. subapenninum* specimens in various Italian museum collections. MSNTUP I 15892 is composed by most part of the cranial and post-cranial skeleton, GAMPS 62 M is represented by a few isolated cranial remains and most part of post-cranial skeleton. The other two specimens (GAMPS 63 and 64) are more incomplete than the others because they are only composed by thoracic vertebrae and fragmented ribs.

They are characterized by an increase in body and tusk size and a dorsal broadening of the nasal process of the premaxilla. According to recent data on morphology of *M. subapenninum* tusks, the discovery of two tusked specimens supports the hypothesis that the dimorphism variation in tusk size does not represent sexual dimorphism.

Another study has been carried out on the application of Ground Penetrating Radar (GPR) in vertebrate palaeontology. In particular, the discovery of the previously described *Metaxytherium* specimen (MSNTUP I15892) detected by GPR method has been reported. The application of GPR technique allowed to detect most of the bones of the skeleton (skull, mandible, vertebrae and ribs) in correspondence of a large reflective zone. Other bones (a body of a cervical vertebra, humerus, scapula and caudal vertebrae) were found in correspondence of some smaller reflective zones of high back scattered energy. Each bone was located in a detailed excavation map, in order to compare its position with the spatial distribution of reflective zones.

The success of this application was probably favoured by good geological conditions and by massive and dense bones of this animal and the results obtained in this study can represent a significant contribute to improve and to encourage the using of GPR in the palaeontological field research of fossil vertebrates.

Riassunto

Nella prima parte della presente tesi di dottorato è stato svolto uno studio geologico-stratigrafico, tafonomico e paleoecologico in quattro aree ubicate nella parte meridionale della Toscana, e precisamente tra le provincie di Grosseto (Arcille e Monte Antico) e di Siena (Poggio alle Mura e Camigliano). Queste aree ricadono all'interno del Bacino di Cinigiano-Baccinello, una depressione che si sviluppa in senso N-S, delimitata ad ovest dalla dorsale Monticiano Roccastrada e ad est dall'allineamento Montalcino-Monte Amiata-Monte Labbro. Le successioni sedimentarie studiate sono riferibili al Pliocene inferiore ed, in particolare, alla parte bassa dello Zancleano (5.08-4.52 MdA)

Dal punto di vista paleoambientale, le quattro sezioni stratigrafiche affioranti nell'area di studio sono caratterizzate alla base da sedimenti riconducibili ad un sistema deltizio, che vengono progressivamente sostituiti da sedimenti argillosi riferibili ad un sistema di piattaforma esterna. La parte centrale delle sezioni stratigrafiche è caratterizzata da sedimenti sabbiosi in cui si osservano shell-beds lateralmente continui in corrispondenza dei quali sono stati rinvenuti resti di vertebrati marini (bonebeds). In particolare, nella sezione di Arcille, sono stati scoperti tre scheletri più o meno completi di *Metaxytherium subapenninum* (Mammalia:Dugongidae) in associazione ad un gran numero di altri resti di vertebrati come, ad esempio, numerosi denti di squalo. Nelle sezioni di Poggio alle Mura, Camigliano e Monte antico sono stati rinvenut uno scheletro quasi completo di un grosso Misticeto, un omero di *Metaxytherium subapenninum* e alcune vertebre articolate di un Odontoceto; anche in questo caso sono stati osservati numerosi denti di squalo ed altri resti di vertebrati strettamente associati ai resti scheletrici dei mammiferi marini.

Sulla base di analoghe caratteristiche stratigrafico-deposizionali e sulla base dello studio tafonomico condotto sulla fauna fossile, è stato possibile correlare le quattro successioni studiate. In particolare, i livelli in cui sono stati rinvenuti i resti di vertebrati marini associati agli shell-beds sono stati interpretati come dei depositi condensati. Tali depositi rappresentano un momento in cui è avvenuto il massimo rallentamento nella sedimentazione e sono associati a superfici di trasgressione che marcano il passaggio da un ambiente ancora influenzato dal continente (sistema deltizio) ad uno in cui si istaurano condizioni francamente marine (sistema di piattaforma esterna).

La seconda parte della tesi ha riguardato lo studio sistematico di quattro reperti di sirenii rinvenuti nella località di Arcille (MSTUP I15892, GAMPS 62, 63 e 64M). Tale studio ha permesso di riferire tutti i reperti alla specie *Metaxytherium subapenninum*

Lo studio sistematico è cominciato con la raccolta dei dati morfometrici su tutti i reperti di *M. subapenninum* scoperti in passato e attualmente custoditi presso alcuni musei italiani. I reperti studiati sono:

- MSNTUP I15892

Tale reperto è attualmente custodito presso il Museo di Storia Naturale e del Territorio dell’Università di Pisa ed è costituito sia dallo scheletro craniale che da quello post-craniale.

Il cranio, quasi completo, è costituito dai premascellari, con entrambi gli incisivi infissi nei rispettivi alveoli, i mascellari incompleti, i nasali in connessione con i frontali e i parietali, e un frammento isolato del sopraccipitale. Sono inoltre presenti l’arco zigomatico destro completo (costituito dallo jugale e dal processo zigomatico dello squamoso), quello sinistro incompleto costituito solo da un frammento del processo zigomatico dello squamoso, entrambi i processi post-timpanici dello squamoso (sebbene il destro sia rappresentato solo da un piccolo frammento) e, infine, entrambi gli esoccipitali quasi completi.

Le mandibole sono entrambe presenti: la destra è incompleta poiché è mancante la parte posteriore e conserva il quinto premolare (dp5) e tutti e tre i molari (m1, m2 e m3) infissi nei rispettivi alveoli. (l'm3 non è completamente eruttato). La sinistra risulta quasi completa, mancante per lo più del processo condiloideo e coronoideo, e sono presenti il primo e il secondo molare (isolati) e il terzo molare infisso nell'alveolo e non completamente eruttato. Lo scheletro post-craniale è rappresentato dalle prime due vertebre cervicali (atlante ed epistrofeo) e da un'altra vertebra cervicale incompleta, da alcune vertebre toraciche, lombari e caudali ancora presenti all'interno della matrice rocciosa, e da gran parte delle coste. Sono inoltre presenti l'omero sinistro incompleto la scapola destra incompleta, mancante della fossa sovraspinata.

In questo caso il reperto è riferibile ad un esemplare giovanile e ciò si evince sia dalle dimensioni del corpo relativamente ridotte, dalla morfologia dei denti (il terzo molare inferiore non è completamente eruttato) e dalle epifisi dell'omero non completamente fuse.

GAMPS 62M

Il reperto è attualmente custodito presso il Museo Geopaleontologico del Gruppo "Avis" Mineralogia e Paleontologia di Scandicci (FI) ed è rappresentato da alcuni frammenti del cranio e da gran parte dello scheletro post-craniale. Del cranio sono preservati i parietali in connessione con il sopraoccipitale; alcune parti dell'osso squamoso (i processi post-timpanici destro e sinistro e il processo zigomatico sinistro) e il basioccipitale in connessione con il basisfenoide e il presfenoide. Sono inoltre presenti alcuni frammenti delle ossa uditive (il periotico sinistro incompleto e il timpanico destro anch'esso incompleto). E' preservato inoltre un solo frammento della mandibola sinistra. Sono stati rinvenuti alcuni denti molari sia superiori (M1 e M3 destro e M2 e M3 sinistro) che inferiori (m2 sinistro) e l'incisivo superiore destro.

Lo scheletro post-craniale è rappresentato da quattro vertebre toraciche, tre lombari, una vertebra sacrale e da gran parte delle vertebre caudali. Sono inoltre presenti alcune ossa chevron, gran parte delle coste e lo sterno quasi completo. Il reperto è sicuramente riferibile ad un esemplare adulto anche se probabilmente si tratta di un giovane adulto poiché la radice della zanna risulta aperta.

- GAMPS 63 M

Anche questo reperto è attualmente conservato presso il Museo Geopaleontologico del Gruppo "Avis" Mineralogia e Paleontologia di Scandicci (FI) ed è rappresentato solo dallo scheletro post-craniale. Sono presenti solo sette vertebre isolate in cattivo stato di conservazione e alcuni frammenti di coste. Le ossa sono strettamente associate, ma non in connessione anatomica.

- GAMPS 64 M

Il reperto, conservato presso il Museo Geopaleontologico del Gruppo "Avis" Mineralogia e Paleontologia di Scandicci (FI), appare anch'esso molto frammentario e, analogamente al GAMPS 63 M, è rappresentato solo dallo scheletro post-craniale; sono infatti conservate solo tre vertebre toraciche isolate e alcuni frammenti di coste, tutte strettamente associate, ma non in connessione anatomica.

In un studio recentemente condotto su alcuni reperti di *M. subapenninum,* è stata messa in discussione la possibilità che la specie esibisca un dimorfismo sessuale nella morfologia delle zanne (incisivi superiori). In questo lavoro sono state avanzate cinque ipotesi. In una di queste ipotesi viene considerata la possibilità che la specie non esibisca un vero e proprio dimorfismo, ma che essa sia passata, nel corso dell'evoluzione, da un morfotipo “femmina” ad uno morfotipo “maschio” probabilmente come adattamento alimentare. Sia sulla base di evidenze cronostratigrafiche che morfologiche esibite dai reperti recentemente rivenuti nella località di Arcille, è possibile confermare l’ipotesi suddetta e, cioè che non si possa dimostrare con certezza il dimorfismo sessuale di tale specie.

La terza e ultima parte della tesi ha riguardato l’applicazione di una particolare tecnica geofisica (georadar) finalizzata alla ricerca dei vertebrati fossili. Il metodo georadar è ampiamente utilizzato in campo archeologico, ma è estremamente poco utlizzato nella paleontologia dei vertebrate così come è emerso da un studio bibliografico preliminare.

L’indagine geofisica è stato realizzata nella località di Arcille (Campagnatico, Grosseto) a seguito della quale è stato scoperto uno degli scheletri più completi di *Metaxytherium subapenninum*, oggetto di studio nella presente tesi (MSNTUP I15892).

L’indagine georadar è stata condotta su due aree adiacenti (Area 1 e 2) ed è stata verificata la perfetta corrispondenza tra una area riflettiva piuttosto estesa al centro dell’Area 1 e gran parte dello scheletro del sirenio (il cranio, le due emimandibole, alcune vertebre cervicali e dorsali, e un gran numero di coste). Altre aree riflettive di più piccole dimensioni corrispondono alla posizione in cui sono stati rinvenuti l’omero, una vertebra cervicale, la scapola e altri resti frammentari. Nell’Area 2 le aree riflettive emerse corrispondono, invece, ad alcune vertebre caudali attribuibili allo stesso esemplare. Tuttavia, in corrispondenza di un’altra piccola area riflettiva osservata nell’Area 2 non è stato rinvenuto alcun resto osseo.

Il risultato positivo di questa indigine, pur mettendo in luce la necessità di migliorare tale metodologia per la ricerca di vertebrati fossili, incoraggia e promuove future applicazioni nell’ambito della paleontologia dei vertebrati.

Chapter 1

GENERAL INTRODUCTION

This study has been divided in three principal sections:

I SECTION

In this chapter the study focused on the geological and taphonomic context of two areas located in southern Tuscany (Italy).

The first area is placed in Arcille locality near Grosseto, where a sedimentary succession, up to 30 m thickness, outcrops. This succession is exposed in a small quarry and it consists in early Pliocene shallow marine siliciclastic deposits. Planktonic foraminiferal assemblages allow to attribute the upper part of this succession to the lower part of the Zanclean, in particular to the MPl2 zone of Cita, 1975 dated between 5.08 and 4.52 Ma (age after Lourens et al., 2004). The succession is dominated by yellowish, locally pebbly, sandstone overlain by greysh mudstone. Detailed stratigraphic logs of the quarry face indicate that the sandstone was deposited in a shoalwater deltaic setting. Two decimetric shell and bonebeds (sb1 and sb2) occur at the transition between sandstone and mudstone. These include very fragmented and decalcified mollusc shells, both articulated and disarticulated, and a lot of vertebrate remains. The latters are principally represented by three incomplete skeletons of *Metaxytherium subapenninum* (MSNTUP I 15892, GAMPS 62 M and 63 M), a halitheriine dugongid that lived in the Mediterranean Basin and became extinct in the upper part of the Pliocene because of the progressive climatic cooling occurred after 3.1 Ma (Sorbi et al., 2012). GAMPS 62 M is located a few decimeters above Sb1, whereas MSNTUP I 15892 and GAMPS 63 M are located a few decimeters above Sb2.

The study was started with the description of sedimentary succession: nine lithofacies has been recognized: five of them are actually exposed in the quarry, whereas the last four facies are no presently exposed and they are described on the basis of the work of Lorenz (1968).

The interpretation of these facies allowed to reconstruct the evolution of depositional environments during the early Pliocene. The stratigraphic succession shows an initial regressive event represented by pebbly sandstone and older delta-front sediments deposited during periods of relative falling of sea level. The erosional surfaces, observed in the upper part, suggest the start of a marine transgression that is occurred in response to a relative sea level rise. The stratigraphic interval including the shell-bonebeds marks a period of maximum sediment starving. Finally, the transgressive trend culminates with the massive greyish mudstones.

The taphonomic study has been focused on three specimen of *Metaxytherium subapenninum*:

- MSNTUP I15892 is composed by a nearly complete cranial and post-cranial skeleton: it consists of the skull with tusks, mandibles with teeth, atlas, axis, a body of a cervical vertebra, some thoracic, lumbar and caudal vertebrae, ribs, the left humerus and the right scapula. The bones appear to be disarticulated, but closely associated.
- GAMPS 62M is more incomplete than MSNTUP I15892: it is represented by a few isolated cranial remains, nearly complete vertebral column, a lot of ribs and the sternum. Also this specimen lies in ventral position and the bones are partially disarticulated.

- GAMPS 63 M is represented by a few disarticulated post-cranial remains: it is only composed by thoracic vertebrae and a lot of fragmented ribs.

The associated fauna is composed by invertebrate and vertebrate remains: the formers are essentially represented by several of mollusc taxa dominated by bivalves. Vertebrate remains are essentially represented by a lot of osteichthyes and selachian teeth and bones.

The second investigated area included three sedimentary successions outcropping in three localities (Camigliano and Poggio alle Mura, Siena, and Monte Antico, Grosseto).

Five lithological facies have been recognized and their interpretation allowed to identify a generic transgressive trend. The first unit consists of fine to very fine grey-greenish massive mudstones deposited into low-energy setting; the second unit consist of yellowish matrix-supported conglomerates formed by fluvial processes. The lower part of Unit 3 essentially consists of unstratified matrix-supported conglomerates and they are interpreted as a delta front succession. The middle part of this facies is composed by greenish fossiliferous bioturbated massive sandstones deposited in shoreface environment. The deposition of the upper part of this unit is occurred during a period of a relative rise in sea level followed by a marine transgression. The upper part of this unit is characterized by a laterally continuous shell-bonebed made by tightly-packed molluscs and vertebrate remains; the latters are represented by a nearly complete skeleton of Mistycete discovered in Poggio alle Mura locality, an almost complete left humerus of *Metaxytherium* cf. *subapenninum* (Sorbi and Vaiani, 2007) and some articulated vertebrae of an Odontocete occur in the Camigliano locality.

The taphonomic study is based on the vertebrate remains and the associated fauna:

-Montalcino whale is represented by a nearly complete skeleton of a Balaenidae indet.: most part of neurocranium, a nearly complete mandibular rami, most part of vertebral column (cervical, thoracic, lumbar, caudal vertebrae), and ribs. The bones appear to be disarticulated, but closely associated. The left incomplete humerus is strongly damaged by erosional processes: it is lacking of the head and the lesser tubercle lacks the proximal part, the distal part is nearly complete, but extremely damaged. In the same layer some articulated vertebrae belonging to an Odontocete are also found. The associated fauna is characterized by a well-preserved mollusc fauna, fragments of echinoid tests and spines, foraminifers and large fossil woods. Other vertebrate remains are represented by a lot of fish teeth found closely associated to the whale skeleton and sirenian humerus.

The stratigraphical, taphonomic and palaeocological study performed in these two areas allowed to consider the shell-bonebeds as condensed deposits formed during a period of maximum sediment starving. The shell-bonebeds observed in Arcille and Montalcino successions probably are genetically linked and this hypothesis is also supported by micropalaeontological analyses (both sections have been assigned to *Globorotalia margaritae* Zone (Cita, 1975; Iaccarino 1985) dated to 5.08- 4.52 Ma).

II SECTION

The second section concerned on the systematic study of sirenian specimens. In particular the description has been performed on MSNTUP I 15892, GAMPS 62, 63 and 64 M (these three last specimes previously have been summarily reported by Sorbi et al. (2012)). All these specimens have been referred to *Metaxytherium subapenninum* (Bruno, 1839) Fondi and Pacini, 1974.

Metaxytherium was generalist and cosmopolitan genus widely distributed during the Miocene and it became extinct throughout the world during the late Miocene except along the Euro-North African coasts. Only two species (*M. serresii* and *M. subapenninum*) survived in the Mediterranean Basin during Pliocene: *M. serresii* became extinct in Early

Zanclean, whereas *M. subapenninum* survived until early Piacenzian. A progressive climatic cooling occurred during this period and *M. subapenninum* initially responded to this climatic change increasing its body and tusk size.

Several *M. subapenninum* specimen have been collected since the beginning of the nineteenth century in Italy (only two specimens come from Spain). All *Metaxytherium* specimens, excluding those coming out of Italy, have been personally examined for comparison.

The specimens discovered in Arcille area are described in details in chapter 3. The description confirms the attribution of these specimens to *M. subapenninum* species. A particular attention has been given to the tusk morphology. In fact in a recent study (Sorbi et al., 2012) the authors focused their attention on intraspecific variability of *M. subapenninum* tusks. This variability suggests, by analogy with the living *Dugong,* a probable sexual dimorphism. This hypothesis is not unlikely because a lot of terrestrial and marine mammals show sexual dimorphism. They have identified two "morphotypes" in *M. subapenninum* specimens: "male" morphotype (large tusks, mediolaterally compressed and with closed roots, crown with a nearly triangular surface on the lateral side of apex and completely covered by cementum); "female" morphotype (small enamelled tusks, elliptical in cross-section and nearly completely unworn, apart a small apical portion on the lateral side). Chronostratigraphic positions of the specimens are also considered in this study in order to evaluate the gradual evolutionary increase in tusk size. The authors consider 5 hypotheses, briefly described in this chapter; they conclude that the most likely hypotheses are 3 (evolving sexual dimorphism) and 4 (evolving monomorphism), and that the hypothesis of sexual dimorphism in *M. subapenninum* can not confirm with certitude.

On the basis of the morphology of the tusks preserved in MSNTUP I 15892 and GAMPS 64 M, the present study supports the two hypotheses reported in Sorbi et al., 2012.

III SECTION

In this chapter the study focused on discovery of sirenian skeleton by using a geophysical method called Ground Penetrating Radar (GPR). The results of this application has been recently published in Tinelli et al., 2012.

The application of Ground Penetrating Radar (GPR) in vertebrate palaeontology is very rare, while the GPR technique has been long applied in civil engineering, geological, environmental, forensic and archaeological contexts (Joel, 2009).

As above mentioned, in literature there are a few examples of this application to detect fossil bones (e.g. Bernhardt et al. 1988; Borselli et al. 1988; Gillette, 1992; Gardner and Taylor, 1994; Schwartz, 1994; Gillette, 1994a,b; Meglich, 2000; Main and Hammon, 2003). Other two applications have been also recently performed in Val d’Orlo locality near Castelfiorentino (Florence) and in Lucciolabella locality near Pienza (Siena) by same authors of the recently published work (Tinelli et al., 2012).

This skeleton discovered by GPR technique has been found in Arcille locality (Grosseto, Italy) and it is abundantly mentioned and described in details in the chapter 2 and 3 (the catalogue number of this specimen is MSNTUP I15892 and it is actually kept in the Museo di Storia Naturale e del Territorio di Calci (Università di Pisa).

The GPR survey was performed using the Radar System device of IDS Company©; a monostatic antenna of 200 MHz has been chosen on the basis of the presumable depth where fossil remains could be found. A 0.2 m grid of acquisition was used, and the data were acquired in continuous mode by an odometer wheel.

The investigation area has been subdivided in two areas (Area 1 and Area 2) and the grid system is formed by squares.

After the application of GPR in the areas and after the sequence of data processing, time slices at various depths in Area 1 and 2 indicated the presence of some irregular reflective zones.

The following excavation confirmed that these zones were mostly corresponding to buried bones (all bones have been recorded using an alphanumeric code for each square in order to compare GPR map and the location of fossil remains). Some of the larger reflective zones correspond to bones of the skeleton (skull, mandibles, vertebrae and ribs). Other bones (humerus and scapula) were found in correspondence with some smaller reflective zones of high back scattered energy. Only a few smaller reflections do not correspond to fossil remains (e.g concretionary level might have generated these smaller reflections).

Through interesting results obtained in this study, this test could represent a significant contribute to improve and to encourage the using of GPR in the palaeontological field research of fossil vertebrates.

Chapter 2

GEOLOGICAL AND PALAEOECOLOGICAL SETTING

2.1 GEOLOGICAL, STRATIGRAPHICAL AND PALAEONTOLOGICAL CONTEXT OF THE ARCILLE AREA

The Arcille succession crops out in the south-west area of Baccinello-Cinigiano Basin, a Neogene post-collisional basin located in southern Tuscany (central Italy) (Martini and Sagri, 1993). The basin is filled with 250 m of upper Miocene continental clastic deposits (conglomerates, sands, silty clays) with intervening lignite seams and freshwater carbonates (Benvenuti et al., 1995, 2001) (Fig. 2.1).

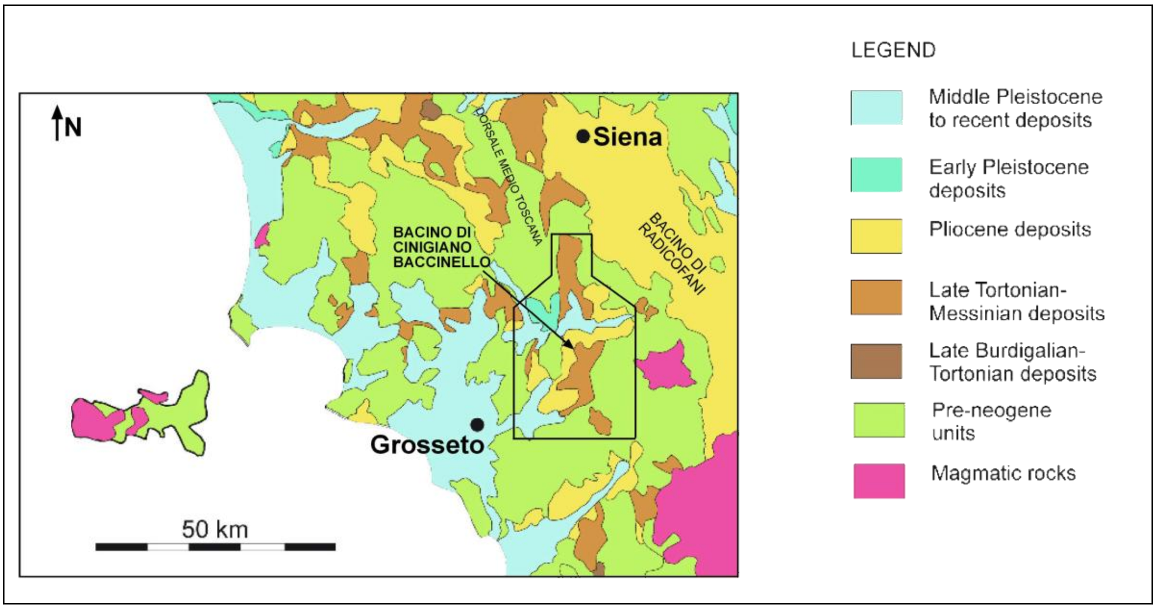

Fig. 2.1 – Geological map of Baccinello-Cinigiano Basin.

The Arcille succession (Fig. 2.2), up to 30 m in thickness, corresponds to a regressive-transgressive episodes belonging to the same stratigraphic cycle. The Arcille succession is composed by nine units: their description is based on a detailed facies analysis carried out in the quarry, where the lower part of this succession is now exposed. The upper part is no longer presently exposed and was considered on the basis of its description by Lorenz, 1968. The author considered a stratigraphic succession outcropping 1 km East-South-East of the Sticcianese, a locality neighbouring the study area. He analyzed in details the sedimentological and mineralogical aspects and the faunal context of the succession with a particular reference to the foraminiferal assemblages.

Fig. 2.2 A datail of outcropped Arcille succession.

On the basis of geographical location of the succession, the description of sediments and faunal content, the succession described by Lorenz, 1968 partially overlaps with the succession exposed in the quarry. The lithofacies, characterized by lithology, colour and faunal content, were formed in different depositional environments. In ascending stratigraphic order they are the following:

UNIT 1

Description – This unit, ca eight meters thick, is composed by a well-sorted medium-fine yellowish sandstone that becomes finer-grained upward. At the lower boundary subhorizontal laminations occur. In the middle part of the unit at ca five meters from the base, there are thin interbeds of yellowish, very fine grained sandstone that are inclined slightly toward south. These interbeds underlie to very fine orange-grey sands. The uppermost part is characterized by joints mineralized in calcium carbonate with an inclinations varying from 20° to 55° predominantly dipping to a West-South-West direction. In correspondence of the uppermost part of this unit rare trace fossils, including mainly *Thalassinoides,* often obliterate sedimentary structures. A disarticulated skeleton (GAMPS 64 M) of *Metaxytherium subapenninum* (Mammalia, Sirenia) probably was found at the transition this unit and the overlying UNIT 2. However, its exact stratigraphic position remains unclear because at the time of discovery the lower part of section was not completely exposed.

Interpretation – The unit represents a shallow marine setting. On the basis of sedimentological features (lithology, sedimentary structures and sorting; Nichols, 2009) and micropalaeontological content, characterized by transported shallow marine foraminifers, this facies corresponds to upper shoreface deposits. The occurrence of *Thalassinoides* is consistent with this interpretation (Seilacher, 2007).

UNIT 2

Description – Unit 2 is three meters thick and rests through a sharp, planar surface over bioturbated fine-grained sandstones of UNIT 1. The surface is marked by aligned coarse pebbles. This facies mainly consists of rounded, ovoid fine pebble gravels (10-15 mm) and coarse pebble gravel (20-30 mm) with a very coarse-grained, well-sorted sandstone matrix (Fig. 2.3). In details, an alternation of decimetric thick orange-grey sandy and pebble gravelly layers is observed. The medium- to coarse-grained sandy layers show an inclined plane lamination. Cross laminations also occur in the sandstone showing a prevalent sediment supply from North-North East. The samples collected for micropalaeontological analyses are barren.

Interpretation – Considering the sedimentary features (alternation of sands and gravels, plane and cross- lamination), this facies, abruptly overlying UNIT 1, has been interpreted as a delta front succession (Ricci Lucchi, 1980). Specifically, the vertical stacking pattern of sandy and gravelly layers suggest high frequency oscillations in the river sedimentary flux. The high energy of delta front setting prevents the development of a foraminiferal assemblage.

UNIT 3

Description – This unit is composed of seven to eight thick fining-upward yellowish sandy succession, separated from UNIT 2 by a deeply erosional irregular surface. The lowermost portion (ca two meters thick) consists of coarse-grained sandstone showing a few centimetres-thick undulating sets of concave-up, cross-laminae (trough cross lamination). Upward colour turns to greyish, the sediment grain-size becomes finer (fine-grained sandstone) and bioturbation increases completely obliterating the sedimentary structures. Some loosely packed shell fragments (not well identifiable), and thin alternate intervals (ca 20-50 cm) of yellowish well sorted silty sands and grey muds are present in this interval. The micropalaeontological analyses of these sediments provide evidence of rare and poorly preserved benthic foraminifers, mainly *Ammonia beccarii*, *Ammonia parkinsoniana* and *Elphidium crispum.*

Interpretation –The presence of shell remains and the evidence of sets of trough cross lamination are typical of a high-energy shallow marine setting corresponding to a shoreface environment (Nichols, 2009; Ricci Lucchi, 1980). In more details, the transition from coarse to fine-grained sandstones suggests the passage from an upper to lower shoreface setting. This interpretation is supported by the occurrence of bioturbation and silty and muddy layers in the upper portion. The foraminiferal assemblage, characterized by shallow marine species, also confirm this interpretation; the presence of the euryhaline foraminifer *Ammonia parkinsoniana* suggests a river influence (Jorissen, 1988; Rasmussen, 2005). The erosional surface separating UNIT 3 from underlying deposits marks the disactivation of fluvial influence.

Fig. 2.3 Decimetric thick orange-grey sandy and pebble gravelly layers within the coarse-grained, well-sorted sandstone matrix.

UNIT 4

Description – UNIT 4 consists of fossiliferous bioturbated muddy sandstones containing abundant shell remains. It is about two-half meters thick and the sandstones are greenish-yellow in the lower part, greyish-yellow in the upper.

In particular this deposit is represented at the base by massive, fine- to very fine-grained, burrowed muddy sandstones in which shell remains are scattered, isolated, or form thin shell concentrations and small pockets. There are also scattered wood fragments and other plant debris.

Two laterally continuous shell beds (lower shell bed=sb1 and upper shell bed=sb2) occur in the medium part of this unit. They are massive, dense shell concentrations, ca 0.20 and 0.50 m thick, revealing a great variety of palaeontological and taphonomic features that are analyzed in detail in this study (see paragraph 2.3). The skeletal remains contained within this deposit are predominantly represented by mollusc shells, but other invertebrate remains are also found. Common vertebrate remains are represented by osteichthyes and selachian teeth and bones, and fish otoliths.

In general, molluscs are found in different states of preservation: it is composed of poorly ordered rounded convex-up and convex-down valves, sandy-filled internal moulds, disarticulated shells that are aligned with bedding; some nesting of shells were found in the thicker sb2, where shell density is higher. In both shell beds bivalves are more abundant than gastropods and scaphopods.

Well-preserved molluscan remains were in the field and from 0,5-1 dm^3-bulk samples. Qualitative taphonomic analyses were carried out.

In the bioturbated muddy sandstones underlying two shell beds, trace fossils are mainly represented by ichnogenera *Thalassinoides* and *Macaronichnus*, which are also common within each shell beds.

Sb1 is characterized by a few, rare and badly preserved molluscan taxa. Few decimeters above sb1 a nearly complete skeleton of *Metaxytherium subapenninum* (GAMPS 62M) was found (for more details see chapter 3). This specimen was discovered together with other vertebrate remains represented by several fish teeth. An isolated vertebra probably referred to a cetacean, and a posterior part of a vertebral column and fin rays of a tuna-like fish were also recovered in the same horizon. Sb1 is separated from sb2 by strongly bioturbated fine sands, about one meter thick, containing dispersed molluscan remains.

Sb2 is represented by a high molluscan concentrations, mostly represented by bivalves and by a few gastropods and scaphopods. Solitary flabellid scleractinian corals (*Flabellum* sp.) form a laterally-continuous bed slightly beneath sb2.

Two *Metaxytherium subapenninum* skeletons (GAMPS 63 M and MSNTUP I15892), one of which (MSNTUP I15892) is nearly complete (see chapter 3), were found few decimetres above sb2. Also in this case sirenian skeletons were found in association with abundant marine vertebrate remains comprising osteichthyes and selachian teeth (see Appendix 1). Sb2 gradually passes upward to fine greyish-yellow sediments (silty sands in the lower part and sandy silt in the upper one) containing a low quantity of invertebrate remains and apparently without vertebrate remains (Fig. 2.4). The micropalaeontological analyses of these sediments provide evidence of a foraminiferal assemblage: the most common taxa are *Ammonia beccarii*, *Ammonia parkinsoniana* and *Elphidium crispum*.

Interpretation – This facies has been deposited in lower shoreface according to sedimentary features (massive, fine- to very fine-grained muddy sandstones, Bosellini et al., 1989). This interpretation is supported by the occurrence of bioturbation typical of shoreface environment (Seilacher, 2007), the bad state of preservation of foraminiferal assemblage according to high energy of the marine setting, and finally, the presence of a lot of mollusc shells. Based on the analysis of faunal content, the taphonomic features of fossil assemblages, and the sedimentological and stratigraphic context, the deposition of this unit might have occurred during a period of a relative rise in sea level followed by a marine transgression. In particular, the stratigraphic interval including the two shell beds with marine vertebrates is considered to mark a period of delta drowning followed by sediment starvation prior to the definitive deactivation and replacement with an outer shelf setting.

The taphonomic and sedimentological context observed in this unit provide a straightforward evidence for condensations of the deposits (discussed later).

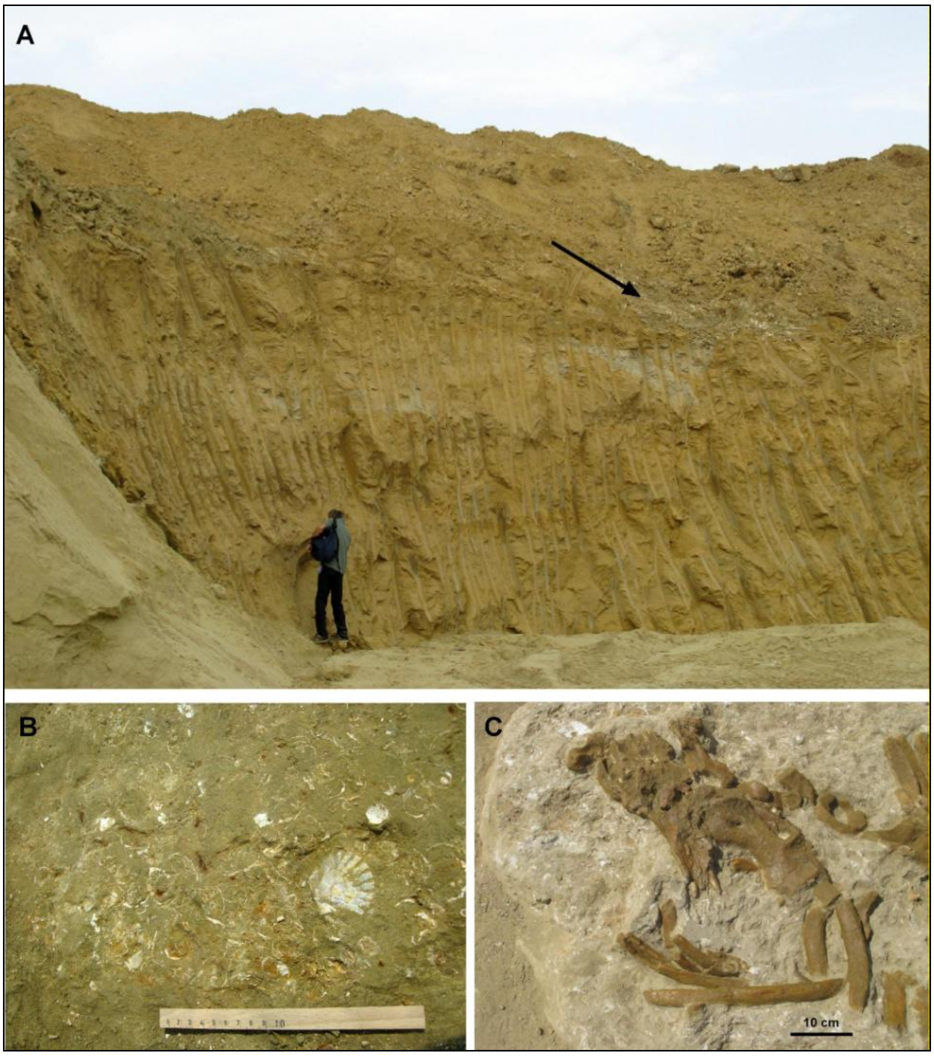

Fig.. 2.4 A) Black arrow indicates the stratigraphic position of the laterrally continuous shell-beds (sb1 and sb2); B) A datail of sb1 (shell-bed composed by poorly ordered rounded convex-up and convex-down valves, sandy-filled internal moulds and disarticulated shells); C) A detail of sirenian skeleton (MSNTUP I15892) found in correspondence of sb2.

UNIT 5

Description – The muddy sandstones (UNIT 4) containing the shell beds grades upward into a massive and thoroughly bioturbated, fine to very fine greyish mudstones (UNIT 5) (Fig. 2.5). The thickness of the lower part of unit exposed in the quarry is greater than six meters. Fractures filled by gypsum crystals, frequently covered by limonite, have been observed throughout the deposit. This unit contains scattered remains of mollusc shells mainly represented by the same taxa found in UNIT 4, but only better preserved. The bivalves are mainly dominated by *Neopycnodonte navicularis* and *Amusium cristatum*; trace fossils belonging to *Thalassinoides* and other unidentified ichnogenera also occur. Vertebrate remains are represented by a lot of fish teeth belonging to the same taxa observed in the underlying unit and some otoliths (they are referred to *Gnatophis mistax* and *Trachyrhynchus* sp.). The micropalaeontological analyses provide evidence of an assemblage that is characterized by benthic and planktonic foraminifers. The former are highly diversified and include mainly *Bolivina*, *Bulimina*, *Cibicides*, *Globobulimina*, *Sphaeroidina* and *Uvigerina*. The latter are represented by *Globigerina bulloides*, *Globigerina falconensis*, *Globigerinoides obliquus obliquus*, *Neogloboquadrina acostaensis* and *Orbulina universa*; among planktonic species a few specimens of *Globorotalia margaritae* have also been found. The first unit mentioned by Lorenz, 1968 shows the same lithofacies described in the UNIT 5 of the Arcille quarry, and the two are considered equivalent. Considering present evidence and data reported by the author the overall thickness of this unit is therefore reported in this study greater than 19 m.

Interpretation – The overall transgressive trend culminates with the massive greyish mudstones deposition that took place in an offshore environment. This interpretation is based on the sedimentary features (fine to very fine greyish mudstones that are massive and thoroughly bioturbated, Bosellini et al., 1989), and palaeontological evidences; Pervasive bioturbations and the ecology of the molluscan fauna (e.g. *Neopycnodonte navicularis*, *Amusium cristatum*) are consistent with an open shelf environment (Pérés, 1989). The micropalaeontological analyses conducted on this deposits provide evidence of one foraminiferal assemblage indicating an outer shelf or upper slope environment characterized by abundant organic matter at the sea bottom, as suggested by the common presence of taxa as *Bolivina antiqua*, *Bolivina dilatata*, *Globobulimina affinis* and *Uvigerina* spp.. The presence of *Globorotalia margaritae* allows the attribution of the upper part of the succession to the MPl 2 zone (from Sorbi et al. 2012).

Fig. 2.5. On the right, massive and thoroughly bioturbated, fine to very fine greyish mudstones of the unit 5.

UNIT 6

Description – This is about one meter thick and formed by fine to very fine-grained massive sandstones. The sandstones grades upward to fine-grained brown-yellowish sands with some white-greyish limonite incrustations. In the lower part the sandstones contain few scattered and poorly preserved foraminifers, whereas, in the upper one, there are rich foraminiferal assemblages in which the best represented species are littoral forms (*Ammonia beccarii*, *Cibicides lobatulus*, *Elphidium crispum*, *Elphidium sp*.); planktonic foraminifers (*Globigerina sp*., *Orbulina universa*) are often found associated together with abundant molluscan shells, ostracods and echinoids.

Interpretation – This unit is regarded as a shoreface environment as revealed by sedimentary features (fine to very fine-grained massive sandstones, Bosellini et al., 1989, Nichols, 2009). The foraminiferal assemblage typical of shallower settings also confirm this interpretation. Finally, this unit can be interpreted as a new regressive trend started after the deposition of UNIT 5.

UNIT 7

Description – This deposit is one meter thick and it is characterized by grey-greenish sandy mudstones where scattered not well-identified foraminifers and ostracods are found. Some glaucony grains are found associated with limonite ones. Fossil assemblage are dominated by the bivalves *Neopycnodonte navicularis* and *Amusium cristatum*.

Interpretation – The thin mudstones of UNIT 7 may be interpreted as forming in a deeper depositional setting with respect to the lower deposits. Fossil assemblages dominating the sandy mudstones consist of *Amusium cristatum* and *Neopycnodonte navicularis*, organisms adapted to low-energy deep environments (Pérés, 1989).

UNIT 8

Description – This unit is six meters thick and it is represented by massive yellowish sandstones. These sandstones are mainly rich of quartz associated with iron oxides and in the lower part no fossil remains are found. These sandstones are interspersed with two thin beds composed by black-greyish slightly marly mudstones (that grade upwards to grey-greenish) commonly associated with thin lignite beds. These thin beds lack of fossils. The upper part of the UNIT 8 consists of very fine yellowish, slightly marly sandstones that are characterized by limonite incrustations and rare fossils remains, especially represented by foraminifers as *Ammonia beccarii*.

Interpretation – The regressive trend continues in the UNIT 8 where the thick massive yellowish sandstones may have formed in a shallow marine setting and culminates in the UNIT 9.

UNIT 9

Description – It is about 1.20 m thick and it is represented by conglomerates consisting of coarse pebbly gravels mainly cropping out in the north-east sector. These conglomerates apparently lack of stratification because the sedimentological structures are badly preserved.

Interpretation – The conglomerates shows a riverine influence. It's very likely that these deposits were formed in a marine environment more shallow than that in which the sandy deposit of UNIT 8.

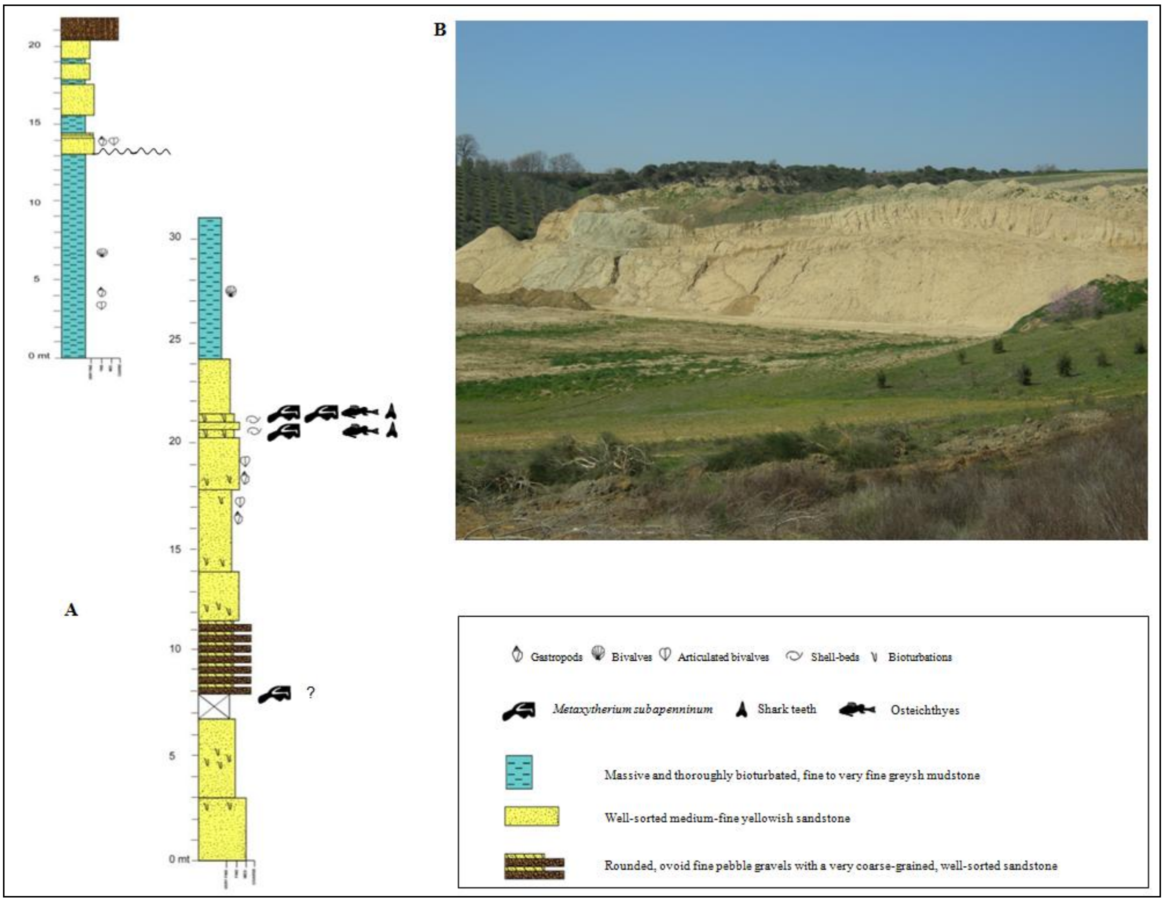

Fig. 2.6 A) Measured stratigraphic sections and stratigraphic position of vertebrate remains; B) A panoramic view of Arcille quarry.

2.2 GEOLOGICAL, STRATIGRAPHICAL AND PALAEONTOLOGICAL CONTEXT OF THE MONTALCINO AREA

The sedimentary successions considered in this study crop out in the north-east of Baccinello-Cinigiano basin, a late Neogene basin located to 25 km east of Grosseto in southern Tuscany. This basin is located in the Eastern part of the Mid Tuscan Ridge, that separated the westward from the eastward central basins during the Late Miocene (Upper Tortonian-Messinian). In the Early Messinian the westward basins underwent marine sedimentation, whereas the eastward, as Baccinello-Cinigiano basin, underwent continental sedimentation. This basin is filled with about 250 m of Upper Miocene continental clastic deposits consisting, from bottom to top, of A) unstratified matrix-supported grey conglomerates and sands; B) fossiliferous silty clays bearing lignite seams; C) fossiliferous coarse sands and gravels fining upwards to grey-red-white banded massive or laminated silts and clayey silts; D’) sandy carbonates rich in fresh water molluscs; D’’) medium-to fine-grained yellow sands locally interbedded with carbonates; E’) polymodal matrix-supported conglomerates; E’’) clast- to matrix-supported conglomerates alternating with massive pedogenized sandy silts (Benvenuti et al., 1994; Benvenuti et al., 1999a,b, 2001, Lorenz, 1968). Sediments of the marine transgression, Early Pliocene in age, unconformably overlay the continental succession of the Baccinello-Cinigiano basin. The deposition of marine units is achieved through two sedimentary cycles: the former consists of a sequence of marine clays and extends from the *Sphaeroidinellopsis seminulina s.l.* Zone to the lower part of *Globorotalia margaritae* Zone; the latter is mainly represented by fossiliferous sands and detritic limestones and evolved during the middle Pliocene (from *Globorotalia aemiliana* Zone to early Villafranchian) (Bossio et al., 1991).

This work presents sedimentological observations and interpretations on three detail sections outcropping in Montalcino area (Fig. 2.7 and referred to the first sedimentary cycle (Early Pliocene in age).

During the course of this study three sections have been measured and described in detailed. They outcrop a short distance from each others: A is located in Poggio Alle Mura (PAM) locality, B in Camigliano (CAM) locality and C in Monte Antico (MA) locality (Fig. 2.7). The sedimentary successions can be divided into five lithological units:

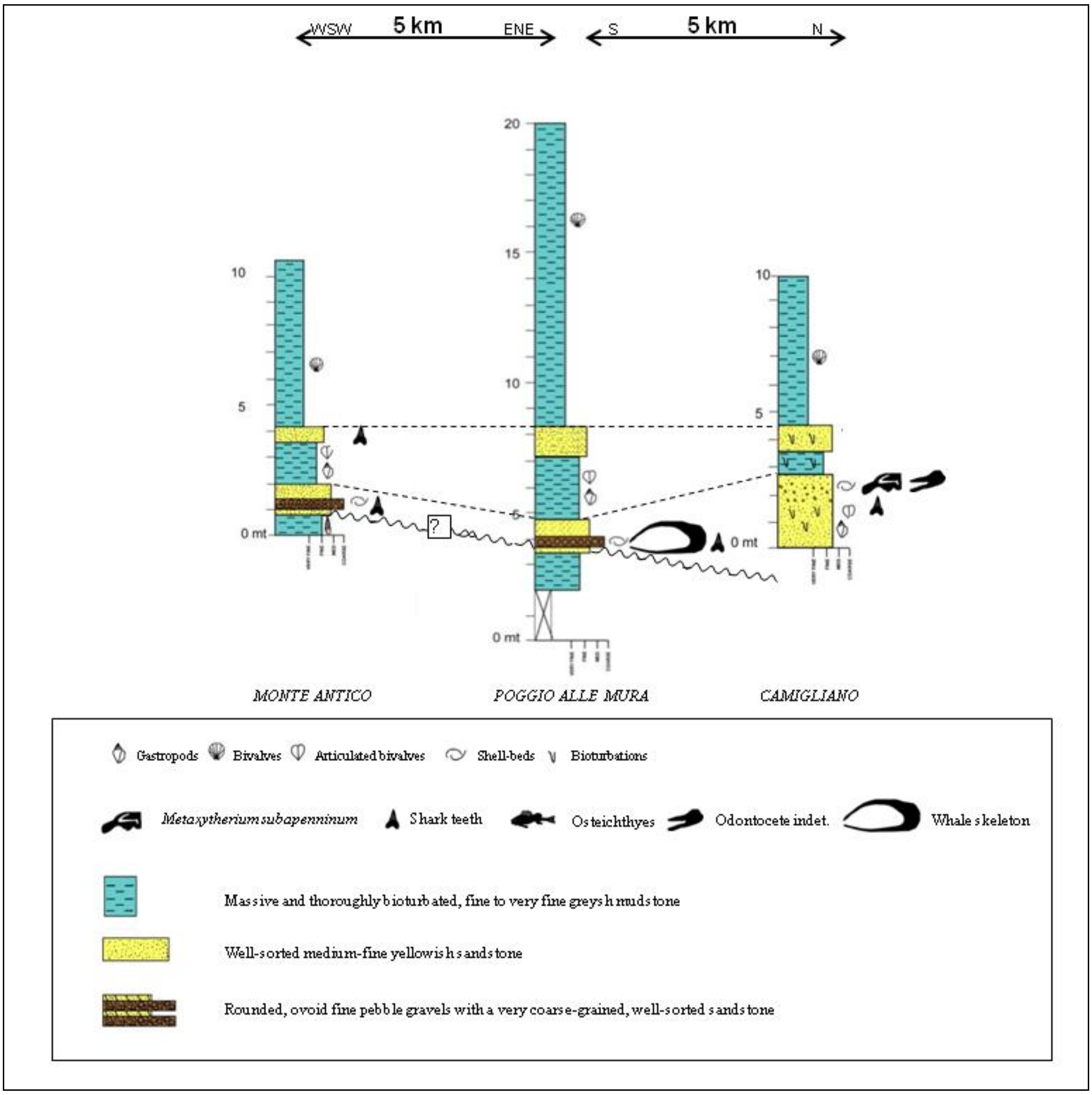

Fig 2.7 Measured of the three stratigraphic successions outcropping in Montalcino area and stratigraphic position of vertebrate remains.

UNIT 1

Description – The unit is actually exposed only in PAM and MA sections. In the PAM section the thickness of this unit is about one meter, whereas in the MA section it is less than one meter. This unit consists of fine to very fine grey-greenish massive mudstones.

The deposit contains rare and poorly preserved foraminiferal assemblages and scattered remains of mollusc shells.

Interpretation – The unit was deposited into low-energy setting. In particular the deposition occurs in an offshore environments and this interpretation is based on sedimentary features (fine to very fine grey-greenish massive mudstones, Bosellini et al., 1989).

UNIT 2

Description – This unit is actually exposed only in the PAM and MA sections and it is about 1.5 m thick. Unit 1 is separated from the coarse-grained deposits of Unit 2 by an erosional surface. The deposits of Unit 2 consist of yellowish matrix-supported conglomerates; these conglomerates are composed of rounded, ovoid pebbles (3-20 cm) and, locally, they show lithodome holes on their surface. Generally these deposits are well amalgamated even if, locally, they are clinostratified.

Interpretation –These conglomerates were formed by fluvial processes. The concordance between dip direction of clinoforms and direction of sediment transport, obtained through the alignments of pebbles, records the progradation of transversal or oblique channel bars (Collinson, 1996; Miall, 1985, 1996,). The low degree of sorting observed within the sedimentary body is probably connected to local variations in hydraulic conditions or flow capacity. The coarsening upward trend is probably caused by the traction transport of the largest pebbles on the bar crest (Nemec & Postma, 1993).

UNIT 3

Description – Unit 3 is composed by greenish fossiliferous bioturbated massive sandstones. Some glaucony grains are found in these sandstones that give them the typical greenish color. At the base these sandstones are fine and become very fine upward ; in the upper part of CAM section, there are also some dispersal rounded pebbles (3 cm). A poorly preserved foraminiferal assemblage occurs in this unit and it is mostly represented by *Ammonia* sp., *Dorothia gibbosa*, *Elphidium crispum*, *Lenticulina cultrata*, *Marginulina costata*, *Nonion fabum*, *Textularia sagittula*. In the lower part of this deposit some loosely packed shell remains have been observed, but they are not well identifiable; On the contrary, in the middle part, mollusc shells are abundant, even if they are often disarticulated and nested. The upper part of this unit is characterized by a laterally continuous shell bed (Fig. 2.8) made by tightly-packed molluscs. Other invertebrate remains are also found including foraminifers, fragments of echinoid tests and spines, some fish teeth, bones and otoliths. Large fossil woods are found too. In correspondence of this deposit some vertebrate remains occur: in particular, a nearly complete skeleton of Mistycete (probably belonging to Balaenidae indet.) together with a lot of shark teeth where discovered in Poggio alle Mura locality. In correspondence of the same level, an almost complete left humerus of *Metaxytherium subapenninum* (see also Sorbi and Vaiani 2007) and some articulated vertebrae of an Odontocete occur in the Camigliano locality.

Interpretation – the lower part of this unit essentially consisting of unstratified matrix-supported conglomerates and they are interpreted as a delta front succession (Ricci Lucchi, 1980). The sedimentary and palaeontological features of this deposit (e.g. dispersal rounded pebbles and poorly preserved foraminiferal assemblage) suggest high energy of the river flux. The middle part of this facies, however, has been deposited in shoreface environment: in particular, the sedimentary features as massive sandstones have observed in the lower shoreface setting (Bosellini et al., 1989). The widespread bioturbation of this part of unit supported this interpretation because it is typical of high energy of shoreface environment (Seilacher, 2007). The palaeontological features (disarticulated and nested mollusc shells) also confirmed this interpretation. The upper part of this unit is characterized by a laterally continuous shell bed: the deposition of this part of the unit, similar to those observed in the UNIT 4 of Arcille succession (see paragraph 2.3.3), is occurred during a period of a relative rise in sea level followed by a marine transgression. This interpretation is supported by the analysis of sedimentological and stratigraphic context and by the study of the palaeontological and taphonomic features. The stratigraphic interval including the shell bed with marine vertebrates is considered to mark a period of sediment starvation subsequent to delta drowning; finally, on the basis of taphonomic and sedimentological features it is possible to interpreted upper part of this unit as a condensed deposit.

Fig. 2.8 Detail of stratigraphic section in Poggio alle Mura locality. The arrow indicates the stratigraphic position of shell-bonebed.

UNIT 3

Description – this unit has different thickness in the three succession (in MA section it is 1.5 m thick, in PAM section it is 3 m thick, whereas in CAM section it is less than one meter). This deposit is characterized by greenish massive mudstones containing scattered mollusc shells dominated by the bivalves *Amusium cristatum* and *Neopycnodonte navicularis*. The micropalaeontological analyses provide evidence of an assemblage that is dominated by benthic foraminifers belonging, for example, to genera *Ammonia*, *Brizalina*, *Bulimina*, *Cibicides*, *Pullenia*, *Uvigerina*, *Valvulineria*; in this deposit, however, the planktonic foraminifers are very rare. Finally, the bioturbation is present throughout the deposit (Fig. 2.9).

Interpretation – The massive greyish mudstones deposition took place in an offshore environment. This interpretation is based on the sedimentary and palaeontological evidences. In fact, the massive greyish mudstones, pervasive bioturbation and the molluscan fauna, dominated by taxa as *Neopycnodonte navicularis* and *Amusium cristatum*, are consistent with open shelf environment (Bosellini et al., 1989; Pérés 1989). Also the micropalaeontological analyses indicate an offshore environment.

Fig. 2.9 Detail of stratigraphic section in Camigliano locality. Contact between greenish massive mudstones of the unit 3 and massive and thoroughly bioturbated fine to very fine yellowish sandostones of the unit 4.

UNIT 4

Description – The greyish mudstones of the unit 3 grades upward into a massive and thoroughly bioturbated, fine to very fine yellowish sandstones (Fig. 2.9). This deposit is about one meter thick in overall sections and it is characterized by scattered and poorly preserved mollusc shells specially dominated by *Amusium cristatum*. These sandstones are also thoroughly bioturbated. A poorly and badly preserved foraminiferal assemblage occurs in this deposits, but foraminifers are not well identifiable.

Interpretation – these sandstones are typical of lower shoreface environment according to sedimentary and palaeontological features (fine to very fine yellowish sands, widespread bioturbation and the bad state of preservation of molluscan fauna and foraminiferal assemblage).

UNIT 5

Description – The last unit outcropping in the Montalcino area is characterized by massive and thoroughly bioturbated, fine to very fine greyish mudstones. The maximum thickness of this unit is exposed in PAM and it is greater than twelve meters, whereas this deposit is about five meter thick in MA and CAM sections. This unit contains scattered remains of mollusc shells mainly represented by the same taxa found in unit 3 even if they are better preserved. The micropalaeontological analyses provide evidence of an assemblage mostly characterized by benthic foraminifers belonging to genera *Ammonia*, *Brizalina*, *Bulimina*, *Cancris*, *Cibicides*, *Nonion*, *Pullenia*, *Textularia*, *Uvigerina* and *Valvulineria*; the planktonic foraminifers are very rare and foraminifers are not identifiable.

Interpretation – The evident transgressive trend observed through the successions culminate with the massive greyish mudstones deposition. These mudstones may be interpreted as forming in a deeper depositional setting, and in particular in offshore environment. These interpretation is based on sedimentary and palaeontological features that are consistent with an open shelf environment (Pérés, 1989) (fine to very fine greyish mudstones that are massive and thoroughly bioturbated, Bosellini et al., 1989, pervasive bioturbations and the ecology of the molluscan fauna adapted to low-energy deep environments (e. g. *Neopycnodonte navicularis*, *Amusium cristatum*).

2.3 TAPHONOMY AND PALAEOCOLOGY

2.3.1 MATERIAL AND METHODS

For the taphonomic study a different approach has been performed in two areas object of study:

- In Arcille area, the taphonomic study is principally based on the area where MSNTUP I 15892 where excavated. Regard to the other sirenian specimen (GAMPS 62, 63 and 64M) a qualitative study was principally performed through the collection of pictures done during the excavation in order to reconstruct the relative position of skeletal elements.

The excavation of the sirenian remains was conducted following the standard procedure for macrovertebrate collecting (Borselli and Cozzini 1992; Greenwald, 1989; Leiggi et al. 1994). Firstly all bones were partially exposed on the surface and strengthened with a reversible polyvinyl acetate consolidant, then the blocks of sediment containing one or more associated bones were partially isolated from the surrounding rock digging trenches around them. Once a fossiliferous block was isolated, fossil bones were covered with a layer of wet paper towels. Burlap strips soaked with plaster were placed one at a time on the block. After the plaster was hardened the block was undercut and completely separated from the surrounding rock. To collect the largest block (2.0 X 2.0 X 0.5 m), containing most of the sirenian bones, we made a steel-and-wood frame and we covered the plaster-jacketed block with polyurethane. Finally, this large block was transported to the museum by grab truck.

The fossiliferous area where the sirenian skeleton was discovered was mapped using a grid (4.0 X 3.0 m) subdivided in squares (0.40 X 0.40 m): the position of all bones was recorded using an alphanumeric code for each squares (Fig. 2.10). All bones were photographed both in the field and in the laboratory.

Samples of sediment adjacent to the bones were collected and labelled to study associated fauna. Each sample is recorded with the same alphanumeric code used for locating the position of bones.

All samples, ranging from 0.5 to 1.0 litres, were wet sieved through a 1 mm screen; the residue was sorted through a binocular microscope in order to study the biogenic components as, for example, molluscs, echinoids, fish teeth and otoliths. Molluscs were determined at the species level when possible.

- In Montalcino area, the taphonomic study was principally based on the collection of sample of sediments in correspondence of sedimentary sections (CAM, MA and PAM successions) in order to study the associated fauna. A particular attention was paid on those fossiliferous levels where vertebrate remains were discovered. Also in this case the samples, ranging from 0.5 to 1 litres, were wet sieved through a 1 mm screen and the residue was sorted through a binocular microscope.

A qualitative description was done on the nearly complete skeleton of Mistycete excavated at Poggio alle Mura locality during March 2003. This study was principally based on the collection of pictures through which it has been recostucted the relative position of skeletal elements.

2.3.2 TAPHONOMY OF THE ARCILLE AREA

BONE ASSEMBLAGE

MSNTUP I 15892 is discovered in a sun flower field a few meters far from the Arcille quarry where the other sirenian specimens (GAMP 62 M and 63 M) were found. GAMPS 62 M were discovered a few decimetres above shell bed 1 (sb1), whereas MSNTUP I15892 and GAMPS 63M were found a few decimetres above shell bed 2 (sb2). All specimens have been referred to *Metaxytherium subapenninum* (see chapter 3).

- GAMPS 62 M

This specimen was discovered in 2007 and it is partially complete: it is represented by a few cranial remains (parietals, supraoccipital, right and left post-tympanic processes, left zygomatic process of squamosal, basioccipital, basisphenoid, presphenoid, incomplete left periotic and right tympanic, left mandible and some teeth). The cranial remains have been found completely displaced by their original position a scattered compared to the post-cranial bones. The post cranial skeleton lies in ventral position and it is well-preserved: the vertebral column is represented by four posterior most thoracic vertebrae, three lumbars, one sacral and posterior most caudals. All vertebrae are partially articulated. Some chevron bones were found near to caudal vertebrae. The rib cage is almost complete and the thoracic vertebrae are connected to the tuberculum and capitulum of corresponding ribs. The anterior part is badly preserved compared to the posterior one. Almost all of the ribs are in their original position. The sternum is almost complete and it lies on its ventral view above some right ribs.

- MSNTUP I 15892

This specimen was excavated in July 2010 it is composed by bones of a nearly complete skeleton belonging to the same individual (Fig. 2.11). This specimen is referred to *Metaxytherium subapenninum* (see chapter 3).

Using the grid system during the excavation, the entire skeleton is mapped: all bones are preserved in the same level, even if some of them (like some ribs and humerus) are displaced a few cm above and below the level of the rest of the bones. Some skeletal remains are disarticulated but closely associated (*sensu* Behrensmeyer, 1991):

- skull: this bone lies in ventral position and it is strongly damaged probably due to use of plow; it appears to be partially articulated, even if the supraoccipital bone, the right zygomatic arch and the exoccipitals are discovered a few centimetres far from it.
- dentaries: these bones are both preserved and partially complete: the left mandible lies above the right one and they are disconnected to the skull, thus they are displaced from their original position;
- postcranial skeleton: all the bones are disarticulated, but still closely associated. The vertebral column is composed by cervical, thoracic, lumbar and caudal vertebrae: atlas and axis are not connected to each others, but the former is about one meter far from the latter. The nearly complete atlas lies in anterior position and it is completely disarticulated to the posterior part of the skull, even if it is near to the exoccipitals. The axis is strongly

damaged and its neural arch is broken and not connected to the vertebral body. It is far from the skull and near to a thoracic vertebra. A body of a cervical vertebra has been

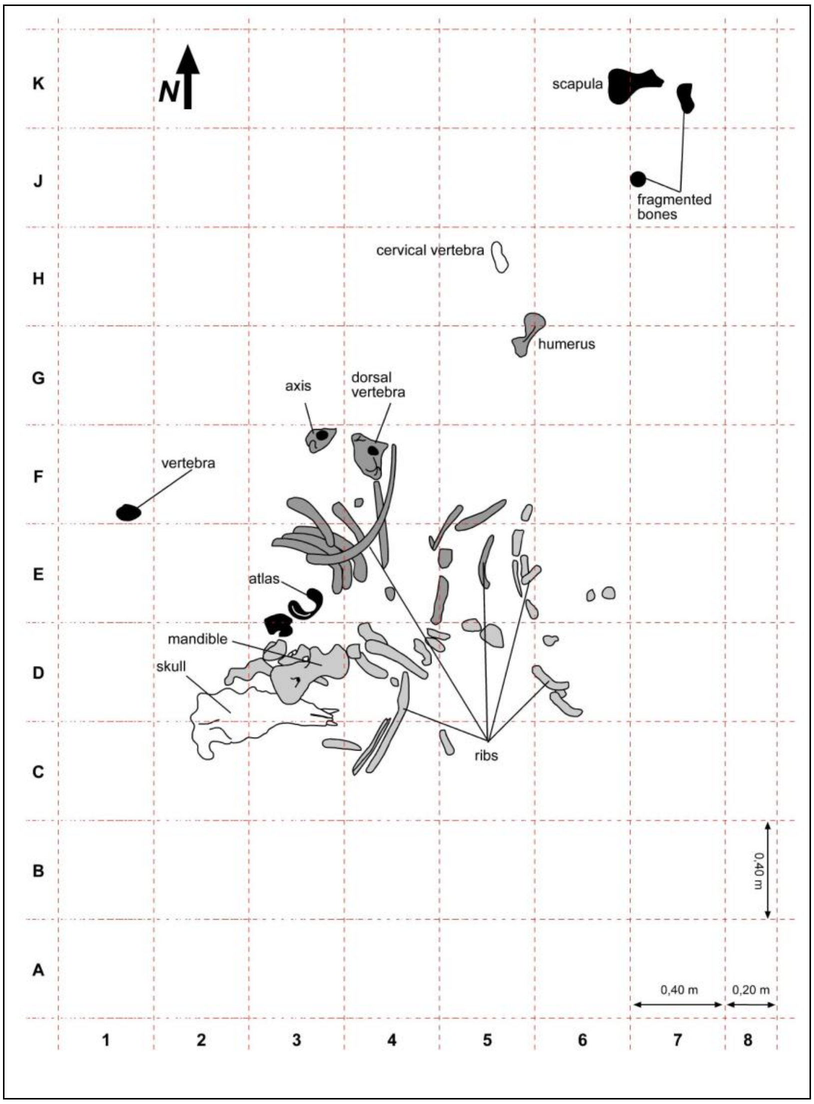

Fig. 2.10 Map view of MSNTUP I 15892 skeleton: the grid system utilized during the exavation was used for mapping the skeletal remains (the postion of each bone was recorded by an alphanumeric code.

found near to the humerus, the latter located more than 0.50 m far from axis. Some thoracic vertebrae, not completely exposed, are near to the rib cage, but they are directly connected to the ribs. The lumbar vertebrae are strictly associated to the thoracic ones, but all vertebrae are displaced to their original position. A few caudal vertebrae lie far from the rest of vertebral column. A lot of the rib fragments have been discovered in the excavation area: some of them appears to be heavily damage and displaced, the others are well preserved, aligned and nearly in life position. The rib cage is displaced a few cm above the level of the rest of skeleton. The apendicular skeleton is represented by an incomplete right scapula and a nearly complete left humerus. These bones have been found far from the rest of the skeleton: in particular, the humerus lies near to the axis and a thoracic vertebra, and it is displaced a few cm below the level where the skull lies. An unfused epiphisis is located near to the scapula that is 1.5 metres far from the humerus. The scapula is located at the same level where humerus lies: it is not complete lacking of most part of supraspinous fossa.

Fig. 2.11 Nearly complete skeleton of MSNTUP I 15892 found above sb2 : skeletail remians are disarticulated, but closely associated.

GAMPS 63 M

As GAMPS 62 M, also this specimen was discovered in 2007. In contrast to MSNTUP I 15892, this GAMPS 63 M is represented by a few bones; in fact only seven cervical vertebrae and a lot of fragmented ribs have been found. These bones are not in their original position and are disarticulated, but still closely associated.

ASSOCIATED FAUNA

A lot of invertebrate and vertebrate remains have been collected and some of them have been found closely associated to the sirenian bones (Fig. 2.12). The skeletons lies few decimetres above two laterally continuous shell-beds (sb1 and sb2, see paragraph 1.1). The shell-beds are characterized by a different mollusc concentration, nevertheless the molluscs are represented almost entirely by sandy-filling internal moulds. Their state of preservation is bad and only a few taxa have been determined at the level species, listed in Appendix 1. Sb1 is characterized by rare and badly preserved molluscan taxa (especially sandy-filling internal moulds), represented by *Cardium hians*, *Venus multilamellata*, *Chlamys sp*. Sb2 is represented by a high molluscan concentrations, but similarly to sb1, fossil remains are mainly dominated by sandy-filling internal moulds. Sb2 is mostly represented by bivalves as *Amusium cristatum*, *Cardium hians*, *Chlamys* sp., *Dosinia exoleta*, *Dosinia* sp., *Glossus* (*Glossus*) *humanus*, *Glycymeris insubrica*, *Ostrea* sp., *Panopea* sp., *Pelecyora gigas* and *Venus multilamellata.* Among gastropods only two taxa were recognized (*Naticarius* sp. and *Aspa marginata*) and one scaphopod species was found (*Dentalium sexangulum*). Evidence of bioencrustion and bioerosion on shell remains is apparently absent. Solitary flabellid scleractinian corals (*Flabellum* sp.) was found slightly beneath sb2. Also in this case sirenian skeletons were found in association with abundant marine vertebrate remains comprising osteichthyes and selachian teeth. In particular, a lot of fish teeth was collected near to the skeleton of MSNTUP I15892 and they belong to *Carcharias taurus*, *Carcharhinus* sp., *Galeocerdo cuvieri*, *Sparus* sp. and *Squatina* sp. Some shark-bite marks has been observed on an only

Metaxytherium specimen (GAMPS 63M). Other vertebrate remains are represented by an isolated vertebra probably referred to a cetacean, and a posterior part of a vertebral column and fin rays of a tuna-like fish.

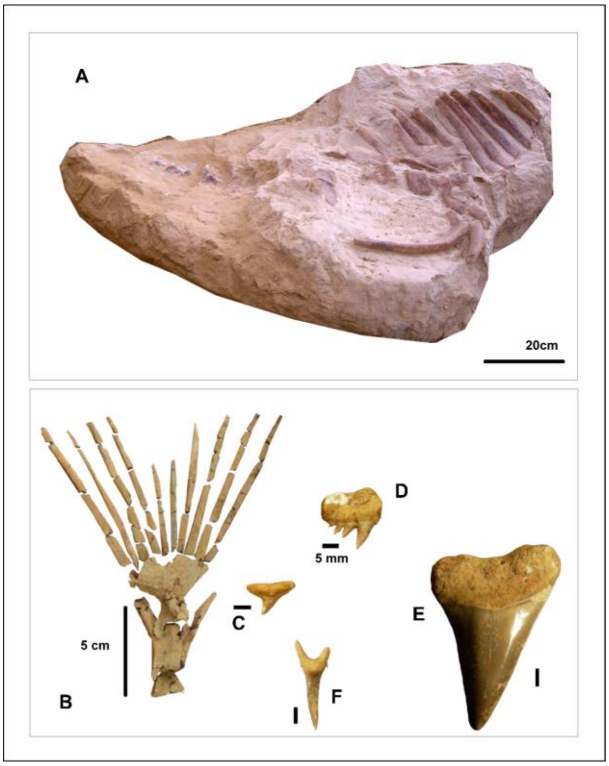

Fig. 2.12 A) Part of the skeleton of GAMPS 62 M; B) posterior part of a vertebral column and fin rays of a tuna-like fish; C) *Charcarhinus sp.*; D) *Hexanchus griseus*; E) *Isurus hastalis*; F) *Carcharias taurus*.

2.3.3 TAPHONOMY OF THE MONTALCINO AREA

BONE ASSEMBLAGE

All vertebrate remains discovered in Montalcino area were found in the same stratigraphic level (UNIT 3) of three successions outcropping in Camigliano, Poggio alle Mura and Monte Antico localities.

The bone assemblage of the Montalcino area is composed by a nearly complete skeleton of a Mysticete (probably belong to a Balaenidae indet.) discovered in Poggio alle Mura locality. An incomplete left humerus (IGF 8743V) belonging to *Metaxytherium* cf. *subapenninum* (Sorbi and Vaiani, 2007) and some articulated vertebrae belonging to an Odontocete were discovered in Camigliano locality.

- MONTALCINO WHALE

This specimen was discovered in February 2007 and it is represented by a nearly complete skeleton (Fig. 2.13). Some bones are partially articulated, whereas others are closely associated. The skull, lying in dorsal view, is discovered a few centimetres far from the post-cranial skeleton and it is composed by most part of neurocranium. Two nearly complete mandibular rami are displaced from their original position a few centimetres far from the skull. The postcranial skeleton is represented by the most part of vertebral column: cervical, thoracic, lumbar, caudal vertebrae are nearly all articulated and some of them lie in ventral view. Most part of rib cage was found and only some ribs are in anatomic connection, whereas other ribs lie far from their original position.

- IGF 8743V is a left incomplete humerus referred to *Metaxytherium* cf. *subapenninum* by Sorbi et Vaiani, 2007. It appears to be strongly damaged by erosional processes. This bone is incomplete lacking of the head, the greater tubercle is well-developed, whereas the lesser tubercle lacks the proximal part. The shaft is slender due to erosion and the distal part is nearly complete, but extremely damaged.

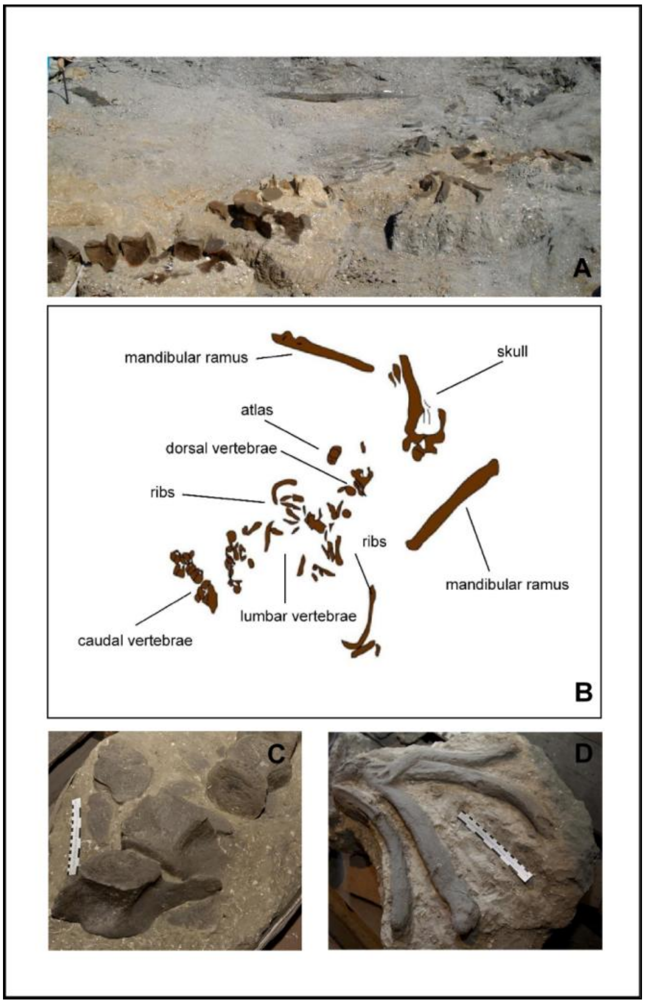

Fig. 2.13 A) *In situ* the skeleton of Montalcino whale exposed after the excavation; B) Map view of whale bones; C) A detail of some lumbar vertebrae of Montalcino whale. and the associated mollusc shells; E) A detail of some whale ribs.

ASSOCIATED FAUNA

The shell-bed is characterized by a high mollusc concentration and the mollusc fauna is well-preserved. A lot of molluscs have been determined at the level species.

The level where vertebrate remains have been found is characterized by a laterally continuous shell bed made by tightly-packed molluscs; in particular, the most abundant taxa are *Dentalium sexangulum* and *Haustator vermicularis*, but there are also *Chlamys multistriata*, *Myrtea spinifera*, *Lucinella divaricata, Nucula palcentina*, *Odostomia* sp., *Ostrea edulis*, *Papillocardium papillosum*, *Timoclea ovata* and *Venus multilamella* (see Appendix 1)

Other invertebrate remains have been are represented by foraminifers, fragments of echinoid tests and spines; finally, a lot of large fossil woods are also found.

Other vertebrate remains are represented by a lot of fish teeth and they have been found closely associated to the whale skeleton and sirenian humeurs. These teeth principally belong to *Carcharias taurus*, *Galeocerdo cuvieri, Isurus hastalis, Carcharhinus* sp., *Sparus* sp. and *Squatina* sp.

2.4 DISCUSSION AND CONCLUSION

The accurate study of Arcille and Montalcino successions allowed to hypothesized that 1) the shell-bonebeds are condensed deposits formed during a period of maximum sediment starving, and 2) the shell-bonebeds observed in Arcille area are genetically linked to those observed in Montalcino area.

A lot of possible causes that could lead to the genesis of vertebrate skeletal concentrations can exist in the record fossil.

Several scenarios of bonebed formation have been envisaged, in both terrestrial and marine settings (e.g.: Behrensmeyer, 1991; Behrensmeyer and Hill, 1980; Brongersma-Sanders, 1957; Martill, 1991; Lyman, 1994; Schäfer, 1962, 1972; Shipman, 1981; Weigelt, 1927, 1989).

For a review, see Rogers et al., 2007. The authors of this works examine the conceptual framework for the genesis and focus their attention on the vertebrate taphonomic modes and methodological approach utilized to explain the general features of a bonebed.

Rogers and Kidwell, 2007 (authors of a chapter of the above cited work) considered both biogenic and physical causes to explain the genesis of bonebeds.

These causes are briefly summarized as follow and they have been discussed in the light of the stratigraphical and taphonomic evidences observed in the marine bonebeds of the Arcille and Montalcino area.

1) *Biogenic concentrations*: they are produced by biological agents or events and they can be intrinsic or extrinsic biogenic concentrations. The intrinsic concentrations result from the activities or behaviours e.g. gregarious behavior) of the vertebrates preserved in the accumulation, although they might be forced by environmental hazard and/or

perturbations. In this type of concentration, therefore, the formation of a death assemblage is primarily due to the behavior or activity of the hardpart producers and it is not the result of action of other organism or physical process.

Extrinsic concentrations are localized accumulations of vertebrate hardparts that are produced by biological agents, mainly activities of other organisms as predators. In this sense the bone assemblage might represent either the result of an active predation or a consequence of a post-mortem bone collecting. According to Rogers and Kidwell, 2007, it is more likely that these types of accumulation are generated in terrestrial environments, especially the bone collecting.

Interpretation: Extant sirenians have gregarious behavior (dugongs may be more gregarious than manatees, see Anderson, 2002) and their ancestors probably had the same social attitude.

Considering this aspect, the presence of sirenian remains in a limited area and the observed formation of bonebeds (the concomitant presence of *Metaxytherium* skeletons in at least two beds) in Arcille succession, could be compatible with the herd behavior of sirenians.

(Furthermore, the palaeoenvironmental reconstruction highlights that most likely the area was close to a zone of high primary activity zone, as inferred from the presence of a nearby river. It is possible that, similarly to the life-style of extant sirenians, a lot of individuals spent most of their time near this area).

Considering the extrinsic concentrations, Rogers and Kidwell, 2007 focused their attention on both predation and post-mortem bone collecting. They are typical of terrestrial environment and, although comparatively few data are available for marine settings with respect to terrestrial ones, it is certain that the bone collecting activity in marine setting is not known.

However, I also considered the trophic interaction between prey and predators: in fact, the presence of bite marks on marine mammals bones due to predatory and/or scavenging activity are frequently observed both in current biological and palaeontological studies (e.g. for the former studies see: Demere`and Cerutti, 1982; Gabriotti and De Maddalena, 2004; Gibson 2006; Heithaus 2001 a,b; Klimley et al., 1996; Long and Jones, 1996; Mc Cosker, 1985; Stillwell and Kohler, 1982; for the latter see: Bianucci et al., 2010; Ehret et al., 2009; Frenguelli, 1928; Lambert and Gigase, 2007; Noriega et al., 2007).

In the taphonomic analysis performed in the present study, there are some shark-bite marks observed on a specimen (GAMPS 63 M) and a lot of shark teeth closely associated to both sirenian and whale skeletons. They were considered as two factors that may have contributed to the concentration of vertebrate remains: the high concentration of fish teeth and bones in a limited area could be explained in the light of the presence of a lot of preys as sirenians. Nevertheless these two factors are not considered here the main cause of formation of bonebeds.

2) *Physical processes concentration*: the vertebrates and their skeletal elements are here considered as sedimentary particles, or “bioclasts” (Behrensmeyer, 1975; Shipman, 1981) and the concentrations are generated by exclusively physical processes.

If vertebrate remains are considered as sedimentary particles, they undergo the same sedimentary events (e.g. transport and deposition) of inorganic particles; concentrations of vertebrate hardparts thus form by the action of surface flows (wind, water, sediment) or wave activity.

Numerous factors can determine the accumulations of vertebrate hardparts, including, for example:

- the energy and persistence of hydraulic agents;
- the amount of bioclastic material delivered to the system;
- the presence of trapping machanisms.

In general, however, independently from the dominance of one of these events, the concentration of vertebrate hardparts is primarily a function of the physical processes and not of the biological agents or events.

Rogers and Kidwell, 2007 reported three examples of physical processes:

1) Fluvial hydraulic accumulations
2) Strandline hydraulic accumulations
3) Sedimentary budget and vertebrate skeletal accumulation

The first two type of accumulation are abundantly discussed in many works (for the first type of accumulation see also Voorhies, 1969; Behrensmeyer 1975, 1982, 1987, 1988; Korth, 1979; Shipman, 1981; for the second type see also Leggitt and Buchheim, 1997; Rogers et al., 2001; Weigelt, 1927, 1989).

Here I principally focused the attention on the third type of accumulation (sedimentological concentration *sensu* Roger and Kidwell, 2007) and I discussed it in the light of taphonomic and sedimentological features observed in Arcille succession.

The relationship between sedimentary budget and vertebrate skeletal accumulation is commonly reported in many works with reference to marine stratigraphic record (e.g. Abbott, 1997; Brett, 1995; Cantalamessa et al., 2005; Fürsich and Oschmann, 1993;

Fürsich and Pandey, 2003; Parras and Casadio, 2005). In particular, these authors considered that a strong association between concentrations of vertebrate hardparts and discontinuity surfaces exists.

The authors focus their attention on the relationship between the concentration of bioclasts and the budget of inorganic material in a generic system; they proposed three sedimentary scenarios and, consequently, three types of concentration:

a) If siliciclastic sedimentary budget is positive, an "obruption" assemblage is formed.
b) If siliciclastic sedimentary budget is negative, a residual lag concentrations are formed.
c) If siliciclastic sedimentary budget is zero, an attritional assemblage is formed.

a) An "obruption" concentration is a concentration formed in a particular circumstance of sediment deposition (e.g. an ash fall) that involves a group of ecologically aggregated individuals; in this case, the assemblage is permanently buried by sediments. This type of concentration depend on both ecological and sedimentary features.
b) A lag concentration is formed when erosion removes sedimentary matrix exhuming larger and/or denser skeletal material.
c) An attritional assemblage is a concentration that is formed during episodes of sediment starvation.

Low sedimentary rates may promote the formation of concentrations of vertebrate material consisting of contemporaneous vertebrate population. On the whole, the longer the nondepositional hiatus, the greater the potential of formation of vertebrate concentrations, thus the richer and laterally more continuous the vertebrate deposit may be (Roger and Kidwell, 2007). In this case, the main consequence of a low or zero net sedimentation is an ecological condensation and amalgamation of skeletal material with diverse taphonomic and sedimentary histories.

From a taphonomic perspective, this scenario has also another implication: in fact, the longer the sedimentary hiatus, the greater the destructive post-mortem event on vertebrate remains.

There are a lot of examples about sedimentary condensation and the impact that it has on the conservation of skeletal remains (e.g. Bown and Kraus, 1981; Brand et al., 2004; Rogers, 1995; Sahni, 1972;). Beds that yield vertebrate and invertebrate assemblages may show different degree of articulation (it is generally low) and this depend mainly on the duration of the hiatus (the degree of articulation will be also linked, for example, to the skeletal structure of animals presented in the assemblage: the stronger the skeletal structure, the lesser the destructive effects on vertebrate remains. This is particularly true for sirenian bones, see below).

Another important aspect of sedimentary condensation concerns the concept of "time-averaging". It is amply discussed by many authors (e.g. Allmon, 1989; Behrensmeyer, 1982; Cutler and Flessa, 1990; Fürsich and Aberhan, 1990; Flessa et al., 1993; Kowalewsky, 1995; Sadler, 1981; Walker and Bambach, 1971); they focused their attention mostly on its scale, causes, and consequence. Kowalewsky, 1995 proposed a review about this topic proposing different types of time-averaging. Considering its absolute meaning, "time-averaging" is defined by the author as "*...the process by which events that happened at different time appear to be synchronous in the geological record...*" (this definition is more general than that proposed by Kidwell and Behrensmeyer, 1993: "*...the process by which organic remains from different time-intervals come to be preserved together...*").

"Time-averaging" is characterized by both extrinsic agents (e.g. vertical mixing, condensation) and intrinsic properties related to the fossil assemblage (preservational potential and abundance) (for more details see the works above cited).

In general, concentrations of vertebrate skeletal remains subject to unusual sedimentation events should show a certain clear evidence of "time-averaging" because all individuals of the assemblage were buried simultaneously (Finch et al., 1972; Roger and Kidwell, 2007; Voorhies, 1985, 1992;). The assemblage should be autochthonous, but in some cases the carcasses may be drift for long distance prior to be definitively buried (it is particularly true for cetacean carcasses that can float for several meters and then decay on the seafloor, thus they are often considered "allochthonous" carcasses. Sirenians, on the other hand, have heavy and massive bones, especially the ribs, and usually are not subject to long post-mortem transport. For this reason they are usually considered autochthonous and their depositional environment represents their living habitat).

Interpretation:

As previously commented, there are two types of physical processes that can form a concentration of vertebrate remains: hydraulic concentrations (that include fluvial hydraulic accumulations and strandline hydraulic accumulations) and sedimentological concentrations (that can generate an "obruption" concentration, a lag concentration and an attritional concentration).

On the basis of taphonomic and sedimentary analyses carried out in the Arcille and Montalcino successions, there are many reasons to exclude that the observed bonebeds are both hydraulic concentrations and the first two types of sedimentological concentrations. The observed bonebeds have not been generated by marine flows (e.g. marine currents), because there is no sedimentological evidences and, from taphonomic point of view, the vertebrate remains show a relative good degree of articulation and/or association.

Bonebeds are not “obruption” concentrations: in fact, the observed sedimentary structures do not connect to any catastrophic event (e.g. an ash fall) and, once again, the taphonomic analysis revealed a good preservation of vertebrate skeletons, that is not compatible with an abrupt event.

Finally, the genesis of lag concentrations are connected to erosional events and the sedimentary evidence of this phenomenon has not been observed in the study area.

On the whole the taphonomic and sedimentary features in the Arcille and Montalcino areas have thus recorded episodes of sediment starvation.

The are some evidences that reveal the condensation of this deposit and they are:

- well sorted, winnowed sand matrix compared with the massive muddy sandstone under the shell beds (Kidwell, 1988);
- combination of specimens characterized by different state of preservation, life stages, and ecologies: shell beds contain predominantly infaunal molluscan assemblages, but epifaunal molluscs are also present. This mixture of different specimens and different ecologies is interpreted as indicating of time-averaging (see Walker and Bombach, 1971).
- the high degree of fragmentation and disarticulation of shells along with moderate biotubartion of enclosing matrix suggests that molluscan hardparts experienced extensive reworking. In low net sedimentation rates conditions, encrusters and borers would have more time to colonize the shells. However, in this case, the low degree of infestation on shells due to colonizers may be due to different causes, e.g. the presence of soft-bodies encrusters that do not leave fossil record (Parsons-Hubbard et al., 2001; Rasmussen and Brett, 1985) and/or the scarce amount of food resources in the environment (Lescinsky et al., 2002). In addition, many encrusting epibionts can be removed by abrasion within

energetic shallow-marine environments (Meldahl and Cutler, 1992; Meldahl and Flessa, 1990; Norris, 1986), therefore, their biological activity might be hidden by physical disturbance of the sea floor.

Another possible cause of the low degree of biological activity on shell remains might be due to the strong pressure of limpets and echinoids that can remove encrusters in early juvenile stages (Carnevale et al., 2011).

These features also reveal that skeletal material was not rapidly buried but accumulated post-mortem on the sea floor. Despite most of the shell remains shows a relatively low state of preservation typical of low sedimentation regimes, the preservation pattern of invertebrate remains is not similar to that observed in vertebrate ones.

Considering the vertebrate taphonomy, conditions of low or zero sedimentation increase the period that skeletal remains are subject to destructive post-mortem processes. This is one of the disadvantages of sedimentary dilution that might lead to a poor conservation of the vertebrate remains.

In the present study, however, vertebrate skeletons show a good degree of articulation and/or associations.

Unlike the more fragile invertebrate remains, the effects of lowered sedimentary rates might have been less destructive on vertebrate specimens. For example, this effect is most likely linked to the strong structure of sirenian bones; In particular, the bones they are both swollen (pachyostotic) and dense (osteosclerotic), especially the ribs (Domning, 2002) and therefore more resistant than other vertebrate remains discovered in the studied area, like poorly preserved fish skeletons. On the other hand, the patterns of preservation of vertebrate remains are different among the specimens.

The habitat and social behaviour of sirenians (the presumed presence of a nearby river with a high primary activity, the trophic interaction between sirenians and sharks and the gregarious behaviour of extinct *Metaxytherium*) are considered here as possible factors influencing the formation of the bonebeds.

The stratigraphic successions above described show a transgressive trend recognizable from UNIT 2 to at least UNIT 5 in Arcille succession and from UNIT 3 to UNIT 5 in CAM, MA and PAM successions. Considering the succession described by Lorenz (1968), a new depositional sequence was only evidenced at the surface separating UNITS 5-6 (sequence boundary) in Arcille succession.

The integrated approach to the study of successions outcropping in Arcille and Montalcino areas through facies analysis and faunal content allowed to reconstruct the depositional dynamics during the early Pliocene.

Considering in details the high-frequency regressive-transgressive cyclicity observed in both successions, the regressive portions are represented by pebbly sandstone and older delta-front sediments in Arcille succession and unstratified matrix-supported conglomerates in MA and PAM successions, deposited during periods of relative falling of sea level. The observed erosional surfaces suggest the start of a marine transgression that is occurred in response to a relative sea level rise.

One of the most peculiar aspects of this facies analysis regards the shell and bonebed deposited between sandstones and mudstones. On the basis of sedimentological and taphonomic analysis, the thin shell and bonebeds are related to low net rates of sedimentation. In particular, the stratigraphic interval including the shell-bonebeds is considered to mark a period of maximum sediment starving which is followed by the replacement of outer shelf setting.

This consideration led to interpret this deposits as transgressive surfaces, above which a sudden deepening occurred. This deepening is in turn marked by a marine- flooding surface at the transition between sandstones and mudstones.

Ultimately, the shell-bonebeds, associated with significant discontinuites as transgressive surfaces, represent a condensed deposit generated during a stratigraphical hiatus in sedimentation.

This transgressive trend culminates with the massive greyish mudstones of UNIT 5 in both successions (Fig.2.14).

This study allowed to correlate the shell-bonebeds observed in Arcille area to those observed in Montalcino area. On the basis of similar sedimentological, stratigraphical, palaeontological and taphonomic features, these bonebed are genetically linked and thus they correspond to the same episode of sediment starvation. This interpretation is also supported by the results obtained by the micropalaeontological analyses. These analyses allowed a reliable stratigraphical attribution for Arcille and Camigliano sections, which are assigned to *Globorotalia margaritae* Zone (Cita, 1975; Iaccarino, 1985) dated to 5.08-4.52 Ma (according to biocronology of Mediterranean planktonic foraminiferal events by Lourens et al., 1996).

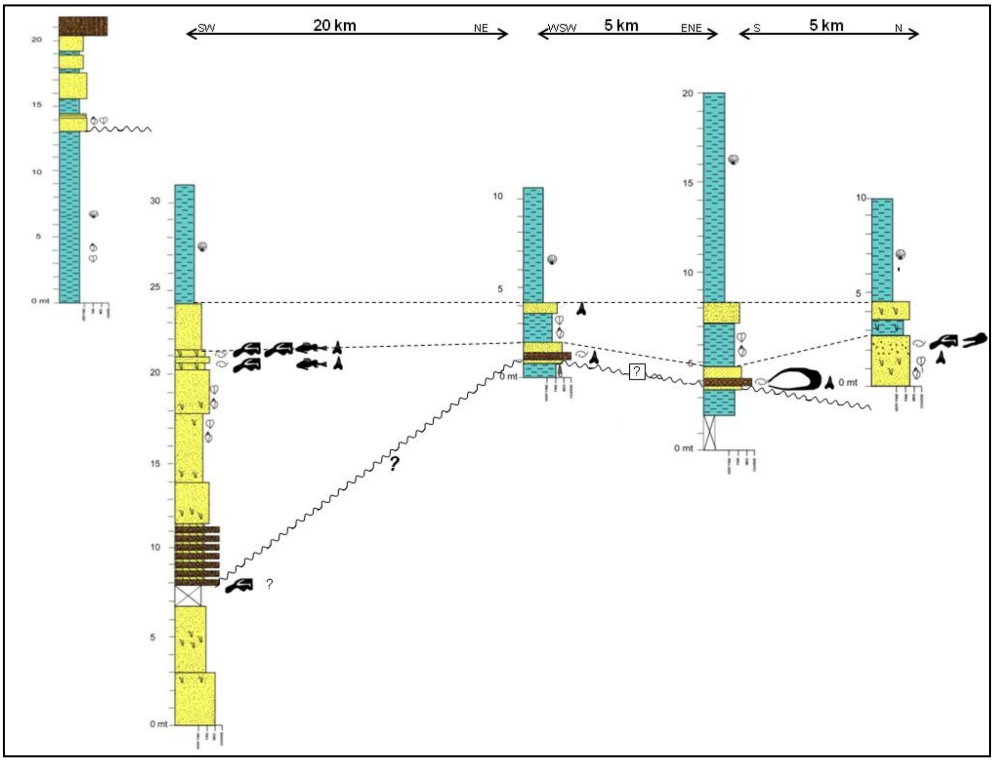

Fig. 2.14 Hypotesis of stratigraphic correlation between studied successions. The shell-bonebed observed in Arcille section (left) is the same observed in Montalcino sections (right). See legend in Figs. 2.7 and 2.8.

Chapter 3

SYSTEMATIC PALAEONTOLOGY

3.1 INTRODUCTION

Metaxytherium was generalist and cosmopolitan genus widely distributed during the Miocene (Aranda-Manteca et al., 1994; Bianucci et al., 2008; Carone and Domning, 2007; Domning, 1988; Domning and Pervesler, 2001, 2012; Domning and Thomas, 1987; Muizon and Domning, 1985; Sorbi et al. 2012). It became extinct throughout the world during the late Miocene except along the Euro-North African coasts; only three species survived: *M. medium* (Tortonian, Sorbi et al., 2012), *M. serresii* (from uppermost Tortonian to early Zanclean, Carone and Domning, 2007) and *M. subapenninum* (from early Zanclean to early Piacenzian, Sorbi et al., 2012). These latter two species lived only in the Mediterranean Basin (Bianucci et al., 2008).

M. subapenninum was recently reviewed by Sorbi et al., 2012 considering its chronostratigraphic distribution, osteology and palaeocology.

In this chapter, I describe in details a new record of *Metaxytherium subapenninum* (MSNTUP I15892) and other three specimen (GAMPS 62 M, 63 M and 64 M), previously reported by Sorbi et al., 2012.

3.2 MATERIALS AND METHODS

MSNTUP I15892, GAMPS 62 M, 63 M and 64 M, all from the Arcille quarry (Grosseto, Southern Tuscany, Italy) have been described in details. Most of *M. subapenninum* specimens from other Italian localities have been personally examined (see APPENDIX) for comparison, whereas the remainder have been studied through literature (Sorbi et al., 2012).

All specimens considered in this study have been measured with a calliper to the nearest millimetre and have been photographed with a digital camera in different standard views (dorsal, ventral, lateral, medial, anterior and posterior).

The anatomical description and measurement follow Bajpai and Domning, 1997; Domning, 1978,1988, Domning and Pervesler, 2001.

All measurements are reported in Appendix 2.

Istitutional abbreviations are the following (* indicates museums personally visited):

DSTG* – Museo Paleontologico dell'Univerisità degli Studi di Genova, Italy;
GAMPS* – Gruppo Avis Mineralogia e Paleontologia di Scandicci, Firenze, Italy;
IGF* – Museo di Geologia e Paleontologia dell'Università di Firenze, Firenze, Italy;
IGPS* – Istituto di Geologia e Paleontologia dell'Università di Siena, Siena, Italy;
MACPM – Museo dell'Asociacion Culturel Paleontologica Murciana, Murcia, Spain;
MC* – Museo Craveri, Bra, Cuneo, Italy;
MCNV – Museo de Ciencias Naturales de Valencia, Valencia, Spain;
MGGC* – Museo di Geologia Giovanni Capellini, Università di Bologna, Bologna, Italy;
MNHN – Museum National d'Historie Naturelle, Paris, France;
MSNTUP* Museo di Storia Naturale e del Territorio dell'Università di Pisa, Calci, Pisa, Italy;
MUSNAF* – Museo di Storia Naturale, Accademia dei Fisiocritici, Siena, Italy;
NHMUK – Natural History Museum, London, England;

NHMB – Naturhistorisches Museum, Basel, Switzerland;

PU* – Museo di Geologia e Paleontologia dell'Università di Torino, Torino, Italy.

3.3 DESCRIPTION

Class MAMMALIA Linnaeus, 1758

Order SIRENIA Illiger, 1811

Family DUGONGIDAE Gray, 1821

Subfamily HALITHERIINAE (Carus, 1868) Abel, 1913

METAXYTHERIUM Christol, 1840

METAXYTHERIUM SUBAPENNINUM (Bruno, 1839) Fondi and Pacini, 1974

Cheirotherium sub-apenninum Bruno, 1839 Mem. R. Accad. Sci. Torino 2(1): 160.

Cheirotherium Brocchii Blainville, 1844 Ostéogr., Genre *Manatus*: 121

Manatus Brocchii (Blainville) Blainville, 1844 Ostéogr., Genre *Manatus*: 121.

Met[*axytherium*]. *Brochii* (Blainville) Laurillard, 1846 Dict. Univ. d'Hist. Nat. 8: 171.

Halitherium Brochii (Blainville) Gervais, 1847 Ann. Sci. Nat. (Zool.) (3)8: 221.

Halianassa Brochii (Blainville) Bronn, 1848 Index Pal.: 562.

Halitherium subapenninum (Bruno) Kaup, 1855 Beitr. Näh. Kenntn. Urwelttl. Säugeth.: 11.

Felsinotherium Forestii Capellini, 1872 Mem. R. Accad. Sci. Ist. Bologna (3)1: 617.

Felsinotherium Gervaisi Capellini, 1872 Mem. R. Accad. Sci. Ist. Bologna (3)1: 634.

Felsinotherium Forestii (Capellini) Lawley, 1877 Atti Soc. Tosc. Sci. Nat. 3: 341-342.

Felsinotherium subapenninum (Bruno) Zigno, 1878 Bull. Soc. Géol. France (3)6: 70.

Felsinotherium Gastaldi Zigno, 1878 Atti. R. Accad. Lincei (Roma), Mem. Cl. Sci. Fis. Matem. Nat. (3)2: 5.

Felsinotherium subalpinum Issel, 1910 Mem. R. Accad. Lincei (Roma) (5)8: 203.

Felsinotherium sp. Issel, 1912 Atti. R. Accad. Lincei (Roma), Mem. Cl. Sci. Fis. Matem. Nat. 9(5): 119-125.

Metaxytherium forestii (Capellini) Fondi and Pacini, 1974 Palaeont. Ital. 67: 37.

Metaxytherium subappenninum [sic] (Bruno) Fondi and Pacini, 1974 Palaeont. Ital. 67: 45.

Metaxytherium gervaisi (Capellini) Fondi and Pacini, 1974 Palaeont. Ital. 67: 45.

Metaxytherium gastaldi (Zigno) Fondi and Pacini, 1974 Palaeont. Ital. 67: 45.

Metaxitherium [sic] *gervaisi* (Capellini) Canocchi, 1987 Riv. It. Palaeont. e Strat. 92(4): 498.

Metaxytherium subapenninum (Bruno) Pilleri, 1988a Contr. Palaeont. of some Tethyan Cetacea and Sirenia (Mammalia): 45-103.

Holotype – PU 13889 - 13890 partial skull and skeleton.

Type locality – Montiglio hills, Tanaro valley, Piedmont, Italy.

Formation – Sabbie di Asti Formation.

Age – Upper part of the Zanclean – lowermost par of the Piacenzian (3.81-3.57).

Referred specimen: See Appendix 2

Range – Lower part of Zanclean to the upper part of Piacenzian, northwester coast of the Mediterranean Basin (Italy and Spain).

DESCRIPTION OF SPECIMENS

1) MSNTUP I15892 (Plates 1-6, Appendix 3)

MSNTUP I15892 excavated in Arcille locality in 2010 is probably a juvenile specimen (m1 and m2 are moderately to heavily worn, but m3 is not completely erupted; the epiphisis of humerus is not fused with diaphases) and it is probably a female ("female" morphotype, see Sorbi et al., 2012). Most part of the skull and mandibles are represented, together with most of post-cranial skeleton (cervical, thoracic, lumbar and caudal vertebrae, ribs, a nearly completed right humerus and an isolated right scapula).

SKULL

Premaxilla – The rostrum is enlarged relative to the cranium and is broken in correspondence of the middle part of mesorostral fossa. It has a thin and sharp dorsal keel anteriorly that broadens posteriorly into a concave surface. The symphyseal portion (it is longer than 10 cm) is raised in lateral view to form a prominent rostral boss. The lateral edges of the rostrum are thin, whereas the sides of its anterior part are flat, but they swell slightly lateral to the tusk alveoli, which extend for nearly the entire length of the symphysis. The nasopalatine canal is elliptical and slightly flattened dorsoventrally. The opening of the premaxillary canal lies posteroventral to the tusk alveoli. Masticating surface of rostrum is trapezoidal in outline. Although the nasal process is not well preserved, it is possible to estimate that its length is longer than half the length of symphysis; furthermore the nasal process contacts the frontals and nasals and, ventrally, it lies in a groove in the maxilla. As noted above, the premaxilla are broken: the posterior end of the mesorostral fossa is rounded and the lateral edges are thin. The rostral deflection is 59°.

Nasal – The well preserved nasals are large, thin and massive. Nasals are set in sockets in anterior margin of frontals and they are separated in the midline of the skull roof by processes of frontals. The dorsal exposure of these bones is elliptical in shape and it has a convex medial border and an anterolateral depression for the nasal process of premaxilla.

Lacrimal – Poorly preserved.

Frontal – The supraorbital processes are partially preserved: only the right process is complete, flattened in a horizontal plane, about 3 cm thick dorsoventrally with a small posterolateral corner. Lateral margin of supraorbital process is not dived by any groove. The frontal roof is relatively narrow and concave between thin temporal crests; the lateral crests are in continuity with the temporal crest of parietals. Medial wall of temporal fossa is formed by a thin lamina orbitalis of frontal, whose falciform anterior edge does not extend forward the posterolateral corner of the supraorbital process. Lamina orbitalis also forms the lateral edge of a large hollow, open anteriorly, whose posterior and lateral walls are probably formed by ethmoid (they are not well preserved in MSNTUP I15892). The internasal process is not well preserved, but it seems to be flat in midline; the nasal incisure is small and it does not extend posterior to the supraorbital process. The frontoparietal suture is well marked and its anterior end lies 5 cm posterior to the nasals, whereas the interfrontal suture is poorly distinct.

Parietal – The parietal roof is deformed and it is broken posteriorly (Fig. 3.1). Nevertheless, it is trapezoidal in shape in coronal section anteriorly, and 3 cm thick in anterior midline. The posterolateral corners of the roof are indented by the squamosal (not well preserved), and the minimum width between these indentation is 75 mm. The parietals are fused to the supraoccipital and the interparietal suture is not clearly evident. The roof is flat and slightly concave between thick lyriform temporal crests. The internal occipital protuberance is distinct but blunt, whereas it is present a small bump in front of external occipital protuberance.

Supraoccipital – Supraoccipital is not well preserved in MSNTUP I15892: it is broken, but fused with a posterior end of the parietal bone. It forms an angle of about 110° with the after part of the parietals The external occipital protuberance rises above the plane of the parietal roof.

Exoccipital – The exoccipitals are complete and they are not fused to each other. The dorsolateral border is smoothly rounded, about 2 cm thick, with a rounded posterior edge that forms a rugose surface at the level of the top of the supracondylar fossa. The fossa is moderately shallow and is located dorso-medial to condyle. The hypoglossal (condyloid) foramen is single. The condyle is oval in shape and the paraoccipital processes, short and with a rugose surface, extend about 2mm lower than the condyles.

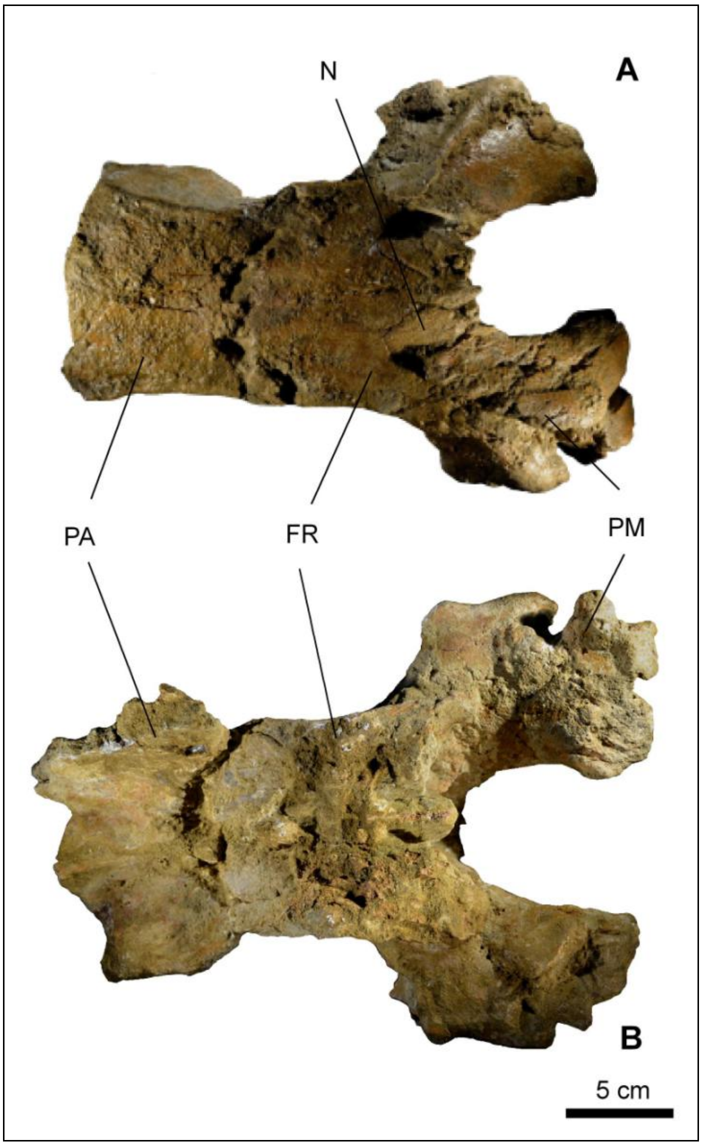

Fig. 3.1 Incomplete skull of MSNTUP I15892 in dorsal (A) and ventral view (B). Abbreviation: PM, Premaxilla, N, Nasal, FR, Frontal, PA, Parietal.

Basioccipital – Basisphenoid – Presphenoid – Orbitosphenoid – Alisphenoid – Pterygoid – Palatine – These bones are not preserved.

Maxilla - This bone is composed only by a small fragment of the left zygomatic-orbital bridge.

Squamosal Only right and left zygomatic processes of squamosal and small fragment of its post-tympanic portion are preserved. The zygomatic processes are nearly complete and they are broader posteriorly than anteriorly; they have a lozenge in shape in lateral view and their medial side are flat. Their posterodorsal edges are slightly convex in outline and anterior tip reaches the level of the posterior end of supraorbital process.

Jugal – Only the right jugal is preserved ant it is nearly complete. The preorbital process is flattened and thin; the ventralmost point lies approximately below the rear edge of the orbit. The zygomatic process, flatted on the lateral side and concave on the medial side, is horizontal and tapered. Raised postorbital process is not present in front of the tip of squamosal.

Mandible – The left and right incomplete dentaries were found closely associated, but not articulated. The condyle is elliptical and overhangs laterally, the coronoid process is broken in both dentaries.The horizontal ramus is dorsoventrally broad and its ventral border, not tangent to the angle, is concave in its posterior portion. On the lateral surface of horizontal ramus there is a small protuberance below m1; its dorsal edge is thin anterior to the tooth row, whereas its anterodorsal margin is sharp . The single mental foramen is very large and it has a deep anterior groove; mental foramen lies at the level of deflection of dorsal edge of ramus. The mandibular foramen is below the m3 alveolus and the mandibular dental capsule opens posteroventrally.

The masticating surface (its deflection is 53°) is partially damaged. It is hearth-shape and rugose; there are the remains of some circular pits that represent the vestigial incisor alveoli, not well distinguishable. Its lateral edges are convex, thin and overhanging.

Periotic – Tympanic Malleus – Incus – These bones are not preserved.

Dentition – The lifetime dental formula of *M. subapenninum* is presumed to be: I 1/0, C 0/0, DP 3/3, M 3/3 (Sorbi et al., 2012).

- Upper cheek teeth:

I - MSNTUP I 15892 preserves unworn tusks fixed in the alveoli. They extend about half length of the symphysis and curve forward. They are long more than 74 mm, about 22 mm wide mediolaterally, and about 26 mm wide anteroposteriorly; the tips, whose distance is about 50 mm, are narrow and slightly rounded and they diverge laterally. An extremely thin layer extends the entire length of the tusks, which present also shallow longitudinal lines on the surface.

DP3-DP4-DP5-M1-M2-M3 – Owing to lack of the ventral part of the skull, upper decidual molars and molars are not preserved.

- Lower cheek teeth:

dp3-dp4 – They are not preserved

dp5 – Right dp5 is fixed in its alveolus and it appears to be heavily worn, rectangular in shape and molariform.

m1 – The left and right m1 are badly preserved: the former is fixed in its alveolus, whereas the latter is found isolated, but closely associated to the right mandible. They are heavily worn and rectangular in shape.

m2 – The left m2 is fixed in its alveolus and the right m2 is isolated. They are rectangular tooth and they are moderately worn (right m2 is less worn than the left one). The protolophid and hypolophid are moderately to heavily worn flat (the protolophid is without cusps) and the transverse valley is moderately deep. The hypoconulid is moderately worn: it consists of four small cuspules and an anterior median spur that block, together with the median ridge, the posterior basin. The hypoconulid has not the tipical 'Y'-shaped form (cfr. Domning, 1988).

m3 – m3 is preserved in both mandibular rami, but it is not completely erupted and it is slightly worn. The protolophid and hypolophid comprise two major cusps and two accessory cusps. The transverse valley is blocked by contact of the protoconid spur and the crista obliqua, that is formed by an accessory cusp of the hypolophid. The hypoconulid is not well preserved, but it seems to be not 'Y' shaped; the hypoconulid of the right m3 preserves two spurs that form the posterior basin (also together with the cusps of hypolophid).

Hyoid apparatus – It is not preserved.

POST-CRANIAL SKELETON

Vertebrae - The specimen is represented by a lot of vertebrae (the vertebral column is not totally preserved): with the exception of the atlas, the axis and another cervical vertebra, MNTUP I15892 preserves some thoracic, lumbar and caudal vertebrae nearly in anatomic connection and partially encompassed in the matrix. Some of thoracics are associated to the ribs too.

Atlas – The first cervical vertebra is found near to the skull near to the occipital bone, but it is not articulate with it. It is nearly complete: the articular surface for odontoid process on the lower arch is well developed, slightly concave; on the contrary, no articular surface for axis is present on the upper arch. The latter is complete and relatively low, and it has two well-marked dorsal and ventral keels. The passage above anterior condyle for first cervical nerve is close on both side; the anterior condyles are concave, relatively large and oval, and they have a thin dorsolateral edge, whereas the posterior condyles are small, flat and they have a ventrolateral edge overhanging.

The left transverse process is complete, whereas the right one is broken: the former is short and slightly posteriorly directed.

Axis – MSNTUP I 15892 preserves the axis, but it is broken in two parts. One part is composed by the odontoid process and the centrum: the former is heavily damaged, but it is visible a depression on its anteroventral articular surface for the ventral arch of the atlas, the latter is rectangular in shape and it has anterior condyles that are oval and convex. The second part is represented by the neural spine that is short, massive and anteriorly directed. The transverse processes are lacking.

Cervical vertebrae (3-7) – The specimen preserves only the centrum of a cervical vertebra, very compressed anteroposteriorly, but it is heavily damaged.

Thoracic vertebrae – Most of thoracic vertebrae were found in anatomic connection and some of these even preserve the articulation with the ribs. They are all encompassed in the matrix. Only one vertebra is well-distinguishable and it is probably an anterior thoracic because two anterodorsal facets of the centrum for capitulum of the ribs are well visible. The centrum is rectangular in sagittal section and it is composed by sponge bone. The transverse processes are short and posteriorly directed.

The neural arch and spine consist wholly of compact bone: the spine is relatively short and it has a pronounced midventral keel.

Lumbar vertebrae – The lumbar series is not complete. The specimen is represented by a few lumbars, that are all encompassed in the matrix.

Sacral vertebra – It is probably not preserved.

Caudal vertebra – The specimen preserves some caudals: they are not found in anatomic position, but strictly associated to each other (they were located near to the skull and far from the block where the other vertebrae were found). They are not well preserved and partially encompassed in the matrix. An isolated caudal shows a flat elliptical centrum and an unfused posterior epiphysis. Both transverse processes and neural arch and spine are completely lack.

Chevron bones – They are not preserved.

Ribs – A lot of ribs were found associated to other post-cranials remains. Some of these appear to be totally complete, but others are heavily fragmented. They are totally or partially encompassed in the matrix.

Sternum - It is not preserved.

Scapula – Only the incomplete right scapula lacking of most part of the supraspinous fossa is preserved. The infraspinous fossa is deep. The spine is quite high, but its distal part is broken. The acromion is not preserved. The glenoid fossa is complete: it is deep, ovoid and broader posteriorly; the supraglenoid tubercle is well-developed. The coracoid process is short and medially directed. The neck is moderately narrow.

Humerus - Only the left humerus is preserved and it is nearly complete. It is robust and relatively short. The proximal epiphysis, about 86 cm wide, is not fused to the diaphysis and it was found a few meters far from it. The tubercles are large and well-developed: the greater tubercle extends proximally to the head and it bears a large anteromedial flange and large rugosities for the insertions of supraspinatus and infraspinatus muscles. The lesser tubercle is inclined proximo-distally. The angle between tubercles is about 71°. Lateral side of neck bears a small protuberance. The deltoid crest is moderately developed and curved as well as the deltopectoral crest, whose distal portion is swelled because of the insertion of the *m. pectoralis major*. Trochlea canted obliquely to shaft at a angle of about 76°; the trochlear articular surface is moderately deep and large, on which a wide notch opens posterolaterally for the insertion of a humeroulnar ligament. Finally both olecranon and coronoid fossa are shallow.

Radius and Ulna – These bones are not preserved.

Manus – It is not preserved.

Innominate – It is not preserved.

2) GAMPS 62 M (Plates 7-10; Appendix 3)

This specimen was found in the same locality where MSNTUP I 15892 was discovered, but few meters far from it and in a different stratigraphic level (see chapter 2).

GAMPS 62 M is represented by a few isolated cranial remains and by most part of post-cranial skeleton, whose bones (vertebrae, ribs and sternum) are partly articulated. It is a young individual because it has an open-rooted tusk (see below).

SKULL

Premaxilla – Nasal – Lacrimal – Frontal – They are not preserved.

Parietal – Although this bone is partially preserved, it appears to be trapezoidal in shape. The parietal roof is thick in midline and anteroposteriorly flat. Interparietal suture is closed but quite evident; the maximum width of parietals below level of roof is about 60 cm. The parietal is fused with supraoccipital and the angle between them is about 120°. The internal and external occipital protuberance are clearly evident and a deep bump is present in front of the external occipital protuberance.

Supraoccipital – Supraoccipital is relatively well preserved and it is 6-sides in outline with rounded dorsolateral corners. The external occipital protuberance exceeds the plane of parietal roof. The median ridge below the protuberance is very strong and increases in height towards its symmetrical ventral border. The nuchal line is low and concave posteriorly and it is marked by a distinct ridge in midline. The rugose areas for the semispinalis insertions extend the nearly entire distance from the external occipital protuberance to the lateral edges of supraoccipital. The lower part is concave in midline in correspondence of either side of the median ridge, and slightly convex laterally. The lateral borders of the supraoccipital are moderately thick and they do not overhang the upper corners. The ratio of width to height of supraoccipital is 1.5. The sutural surfaces for the exoccipitals seem to be separated in the midline with a median notch even if the posterior part of the supraoccipital is badly preserved. Furthermore, the suture with exoccipitals is M-shaped and the central angle is about 122°.

Exoccipital – This bone is incomplete, completely lacking of the condyles. The exoccipitals are not fused to the supraoccipital and they do not meet dorsally in a medially suture. This bone has thick and rounded dorsolateral border and it has also a flat and broad surface oriented anterolaterally.

Basioccipital – It is partially complete being preserved only its right part. The latter appears to be broad and dorsoventrally thin and it has a concave dorsal surface. The ventral surface is flat and it has some rugosities that mark the presence of the insertions of the longus capitis muscles.

Basisphenoid – It is robust and it has a dorsal flat side and a ventral convex side without a median ridge. The sella turcica is broad and shallow and the tuberculum sallae is flat.

Presphenoid – This bone is badly preserved and it is fused with alisphenoid. Only one chiasmatic groove is well visible.

Orbitosphenoid – It is not preserved.

Alisphenoid – Partially preserved but extremely damaged.

Pterygoid – Palatine – They are not preserved.

Maxilla – Only a very small part of this bone is preserved and it corresponds to a fragment on which the left M3 is located.

Squamosal – This bone is represented by the left zygomatic process and by the right and left post-tympanic processes. The former is nearly complete and it is distinctively sigmoid overall: it has a rounded posterodorsal outline and a concave ventral border, and its medial side is markedly flat. The post-tympanic processes of squamosal are also nearly complete: the sigmoid ridge is quite prominent (dorsoposterior margins of the post-tympanic processes are slightly notched above it) and the processus retroversus is moderately inflected and turns ventrally.

Jugal – It is not preserved.

Periotic – The specimen preserved only the left isolated periotic and it appears to be strongly incomplete. A slight groove, partially covered by the border of pars temporalis (tegmen tympani), demarcates the pars temporalis from the pars mastoidea. The anteromedial end of the pars temporalis tapers slightly. The pars mastoidea has a posterolateral edge relatively sharp and its ventral margin is V-shaped.

Tympanic – Only a small fragment of the left tympanic is preserved. It is represented by the distal portion that appears to be V-shaped and with a prominent groove located posteriorly on its medial side. The lateral side is slightly sinuosus (Fig. 3.2).

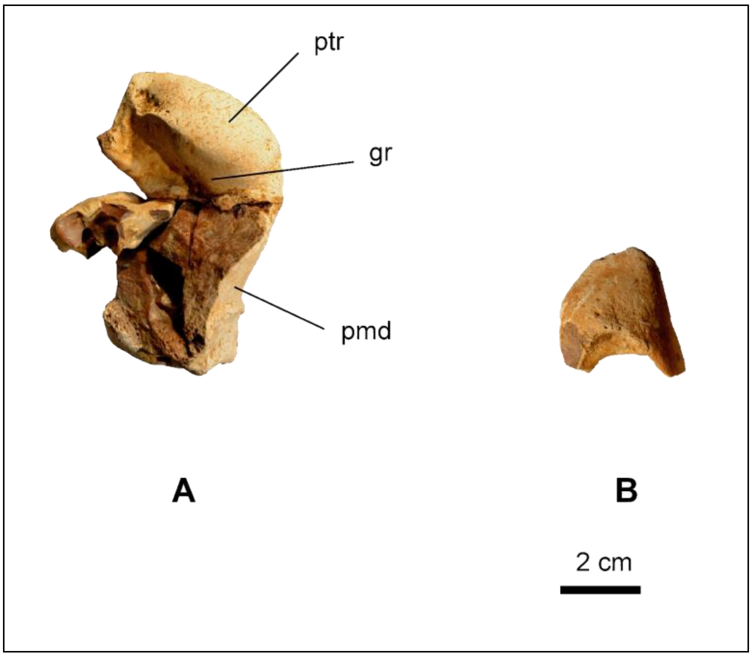

Fig. 3.2 Isolated elements of GAMPS 62M: A) Inferior view of left periotic, anterior at top; B) left tympanic, anterior at top. Abbreviations: gr, groove separating the pars temporalis and pars mastoidea; pmd, pars mastoidea; ptr, pars temporalis.

Malleus – Incus – These bones are not preserved.

Mandible – The specimen preserves only a small portion of the left mandible. It is extremely damaged being represented by a fragmented part of the horizontal ramus. The latter is dorsoventrally broad and its ventral border is slightly concave.

Dentition – GAMPS 62 M does not preserve any teeth fixed in alveoli except for the left M3 that is in own alveolus, anchored in a very small portion of the maxilla.

- Upper cheek teeth:

I – Only an isolated right tusk is preserved (Sorbi et al., 2012:697)

DP3-DP4-DP5 – The are not preserved.

M1 – Only the right M1 is preserved and it appears to be heavily worn.

M2 – The left M2 is partially worn and differs from M1 primarily for its larger size. It is three-rooted even if the root is heavily damaged. The labial side of this tooth is completely worn, whereas the antero-posterior lingual side is moderately preserved. Unworn summit of paracone is subdivided in three picks; the transverse valley is constricted by metaconule as well as by paracone, whose summit is partially worn. A posterior cingular cusp is present.

M3 – Both left and right M3 (Fig. 3.3) are preserved. M3 is larger overall and narrower posteriorly than M2. The precingulum is partially smooth and only an anterior cingular cusp is present; the anterior cingular basin is partially blocked by protocone that is labially larger. Protoconule and paracone are completely worn as well as hypocone. The transverse valley is partially obstructed by metaconule and matacone, whose summit is slightly worn. The postcingulum is composed by three well-developed separate cusps and the posterior cingular basin, opened postero-labially, is completely closed.

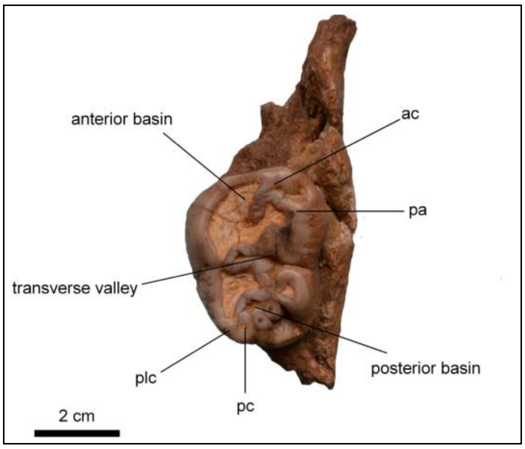

Fig. 3.3 Occlusal view of left M3, GAMPS 62 M. Abbrevations: ac, anterior lingula cusps; pa, paraconule; pc, psterior lingula cusps; plc, posterior lingula cusp.

- Lower cheek teeth:

dp3 – dp4 – dp5 – m1 – They are not preserved.

m2 – It is the only lower molar preserved and it is heavily worn. This molar is rectangular in shape and it is double-rooted. The posterior side is preserved and it is visibile only the postcingulum composed by a posterior cingular cusp. The median ridge and posterior basin are badly recognizable because they quickly lost their identities with wear.

m3 – It is not preserved.

Hyoid apparatus – It is not preserved.

POST-CRANIAL SKELETON

Vertebrae - The specimen is represented by a nearly complete vertebral column. In particular, 16 vertebrae (four thoracics, three lumbars, one sacral, eight caudals) were found nearly in anatomic connection and partially encompassed in the matrix; the specimen is also preserves chevron bones, one of these totally complete.

Cervical vertebrae (1-7) – They are not preserved.

Thoracic vertebrae – The thoracic series is represented only by four posterior-most vertebrae. They were found almost all in ventral position, so only a ventral part of centrum and transverse processes are visible. The thickness of the centrum in midline of three vertebrae are, respectively, 5.75, 6.40 and 6.80 cm (the fourth vertebrae is covered by the third one). The transverse processes are relatively small, posteriorly oriented and slightly rounded. These vertebrae are articulated to the sternum through the ribs.

Lumbar vertebrae – Probably they are the first three lumbar vertebrae (L1, L2 and L3) and they are very similar to the posterior thoracics. Two lumbar vertebrae (L2 and L3) lie in ventral position, while the other (L1) lies transversely to them, partially covering the sternum. The total height of L1 is 19.5 cm (the other two vertebrae have the neural spine totally covered by the matrix). The breadth across transverse processes is, respectively, 51.7, 45.6 and 47.9 cm, whereas the anterior breadth of centrum is 14.8 cm in L1, 15.1 in L2 and 12.8 in L3. The height and thickness of the centrum are, respectively, 8.2 and 7.6 cm in L1, 8.9 and 7.4 cm in L2, and 9.6 and 7.5 cm in L3. The width and height of neural canal are 6.4 cm in L1 and 3.2 cm in L2 (in other vertebrae the neural canal is totally encompassed in the matrix). The maximum length from front of prezygapophyses to rear of postzygapophyses is about 7.4 cm in L1. The transverse processes are slightly ventrally oriented, and more flattened than those of the thoracics.

Sacral vertebrae – Only one sacral vertebrae is preserved and it appears to be nearly complete and in anatomic connection with the anterior and posterior vertebrae.

The distinctive feature of this vertebrae is represented by the transverse processes that are thicker and more downturned than those of the lumbars; the breadth across the transverse processes is about 13.9 cm. The centrum is hexagonal in shape: its anterior breadth is 13.1 cm, whereas its thickness in midline is 6.7 cm; its ventral side is keeled.

Caudal vertebrae – Five caudals (C1-5) are complete and in anatomic connection, the others three are represented by fragmented and scattered remains. C1-5 have a decreasing breadths across transverse processes (from about 33 cm in C1 to 28 cm in C5) as well as a decreasing thickness of centra in midline (from about 7.4 cm in C1 to 67.9 cm in C5). The neural arches and spines are not visible because the vertebrae lie in ventral position. The long transverse processes are very flattened and slightly posteriorly inclined.

Chevron bones – The specimen preserves a complete anterior chevron bone (Sorbi et al., 2012:698).

Rib – GAMPS 62 M does not preserve complete series, but only 11 left ribs and 7 right ribs (the latter are badly preserved); in addiction there are also many fragmented ribs. All ribs are completely pachyostotic except for some cancellous bone in heads. All ribs are nearly in anatomic position and lie in ventral side; Some of the central ribs have very large and very developed tubercola and proximal ends are knoblike; they broaden in the middle part, their shafts become progressively compressed and the angles are no longer distinguishable posteriorly.

The posterior ribs, partially covered by the sternum, are quite small and more compressed in the plane of flattening of the shaft. Three ribs are articulated with the last thoracic vertebrae.

Sternum – The specimen preserves a nearly complete sternum (Sorbi et al., 2012: 699)

Scapula – Humerus Radius and Ulna – Manus – Innominate – They are not preserved.

Manus – The specimen preserves only two fragmented metacarpals.

3) GAMPS 63 M

This specimen was found in the same stratigraphic level of MSNTUP I15892, but, unlike that, it is incomplete and it is represented by only a few post-cranial remains.

SKULL

GAMPS 63 M does not preserve any part of the skull.

POST-CRANIAL SKELETON

Vertebrae - The specimen is represented by only seven thoracic vertebrae that are moderately to heavly preserved due to erosion. Only one vertebra is nearly complete and it is lies in posterior view. Its body is hearth-shaped and its neural spine is oriented posteriorly. Its total height is about 16.9 cm and posterior breadth of centrum is 10.7 cm. The height and thickness of centrum in midline are, respectively, 6.3 and 4.2 cm, whereas width and height of neural canal is about 5.1 and 3.5 cm. The transverse processes are broken. The other vertebrae are represented by fragmented remains and some of these are wholly covered by the ribs (Fig. 3.4).

Fig. 3.4 Vertebrae and ribs: the only preserved bones .of GAMPS 63 M.

Rib – The ribs appear to be heavily damaged by erosion. None of rib is entirely complete, but they are all almost wholly made up of compact bone except for some cancellous bone in heads and distal ends.

Scapula – Humerus Radius and Ulna – They are not preserved

Innominate – It is not preserved.

4) GAMPS 64 M

This specimen was found about fifteen meters below the stratigraphic levels where the other *Metaxytherium* specimens (MSNTUP I 15892, GAMPS 62 M and 63 M) were located. Nevertheless, its exact stratigraphic position remains unclear because at the time of discovery the lower part of section was not completely exposed (see chapter 2).

Similarly to GAMPS 63, this specimen is not complete, but it is represented by a few scattered vertebrae and ribs.

SKULL

The skull is not preserved.

POST-CRANIAL SKELETON

Vertebrae Only three thoracic vertebrae are preserved and they are nearly complete. They probably belong to the anterior part of thoracic series. These vertebrae have posteriorly-sloping

Rib – The ribs appear to be heavily damaged by erosion. No rib is entirely complete (Fig. 3.5), but all are almost wholly made up of compact bone except for some cancellous bone in heads and distal ends.

Scapula – Humerus Radius and Ulna – Manus – Innominate – They are not preserved.

Fig. 3.5 The post-cranial skeleton of GAMPS 64 M is represented by onli three thoracic vertebrae and fragmented ribs: these bones do not lie in their original position.

3.4 COMPARISON

Based on the description of MSNTUP I15892, GAMPS 62, 63, and 64 M, none of these specimens differ in any important anatomical features from the other specimens of *Metaxytherium subapenninum* examined for comparison (see Appendix 1). Nevertheless there are some anatomical characters observed in the specimens above described that are discussed below. The observations were principally focused on MSNTUP I 15892 because the GAMPS specimens have already been described in Sorbi et al., 2012. Furthermore, the comparison is principally based on cranial features, and only a few, but important observations were been done on the post-cranial skeleton of the specimens.

MSNTUP I 15892 differs from the other specimens in having a small length of premaxillary symphysis (166 mm), in contrast to length of 223-188 mm measured in three *Metaxytherium* specimens (MC unnum, MGGC 9160, IGF 13747). Also the length of the frontals in the midline is slightly different between MSNTUP I 15892 and the others specimens: the former has a length of about 86 mm, whereas MGCC 9160 and IGF 13747 have, respectively, a length of 130 and 125 mm. The other specimens have an intermediate length (PU 13889/1 has a length of about 92 mm and MUSNAF 4960 has a length of about 98 mm).

The length of mesorostral fossa measured on MSNTUP I15892 appears to be the lowest with respect to the other specimens (it is about 140 mm in MSNTUP I15892 in contrast with an average length of about 167 mm measured on four *Metaxytherium* specimens).

Considering also the maximum height of rostrum and the anterior and posterior breadth of rostral masticating surface, MSNTUP I15892 appears to be the only *Metaxytherium* specimen that has the lowest values (the posterior breadth of rostral masticating surface is relatively reduced also in GAMPS 62 M).

The mandible of MSNTUP I15892 does not show any significant differences with the other *Metaxytherium* specimens: the only visible feature observed in the left dentary of MSNTUP I15892 is the curvature of horizontal ramus at the level of anterior and posterior ventral extremities; in fact it is appears less curved compared, for example, to MGGC 9160 and IGPS 213. The left dentary of GAMPS 62 M is badly preserved and the only measurements taken on this bone (the distance between anterior and posterior ventral extremities and the top of ventral curvature of horizontal ramus to line connecting ventral extremities) are similar to those of other specimens.

With regard to dentition, both MSNTUP I15892 and GAMPS 62M preserve the upper incisors: in particular the former has two tusks fixed in the alveoli, whereas the latter has an only isolated right tusk. The isolated right tusk of GAMPS 62M is bigger than the tusks of MSNTUP I15892, but it does not differ significantly in other features. Except for MC unnum., all specimens, including those from the Arcille area (MSNTUP I15892 and GAMPS 62M), have tusks slightly curved and subelliptical in shape.

With regard to the tusks, in a recent work (Sorbi et al., 2012) the authors analyze the morphology of upper incisors of *M. subapenninum*. They identify two “morphotypes”: one is characterized by large tusks, mediolaterally compressed and with closed roots; the crown is with a nearly triangular surface on the lateral side of apex and completely covered by cementum. The other morphotype is instead characterized by small enamelled tusks, elliptical in cross-section and nearly completely unworn, apart a small apical portion on the lateral side. The first morphotype is called “male” morphotypes and the second one is called “female” morphotype.

The authors also consider the cronostratigraphic positions of the specimens in order to evaluate the gradual evolutionary increase in tusk size in *M. subapenninum*: the earliest specimens as, for example, IGF 13747 (it is dated to 4.12–3.57 Ma) show small tusks (“female” morphotype), whereas the only latest specimen is MC unnum. (it is dated to 3.19–2.59 Ma) and it correspond to the “male” morphotype. MGGC 9160 represents an intermediate condition because it is dated to 3.81–3.57 Ma and it has the enamel crown of its tusk larger and more flattened than the earliest specimens.

The authors consider five hypotheses (Sorbi et al., 2012: 702-703) that have been described in details, and hereafter summarized and reported below:

- <u>Hypothesis 1</u> consists in considering the two morphotypes as extremes of a continuous spectrum, therefore they should be occurred both in earliest stratigraphic horizons and in the latest ones. Nevertheless no “female” morphotype is known in the latest horizons, thus this hypothesis is not supported by the data.
- <u>Hypothesis 2</u> is related to the sexual dimorphism of *M. subapenninum*: the authors suggest that the species was dimorphic throughout its existence. In this case both morphotypes should occur in equal proportions both in earliest and latest horizons, but, taking in consideration all the specimens with preserved tusks, only MC unnum. (“male” morphotype) is present in the latest horizons. Even this hypothesis is not supported by the existing data.

- Hypothesis 3 is similar to hypothesis 2, but the species would became sexually dimorphic during its existence; in this case only “female” morphotypes should be present in the earliest horizons, whereas both morphotypes should be present in the latest horizons. Considering all the specimens, “female” morphotype is represented in the earliest horizons and only MC unnum. occurs in the latest ones. This hypothesis could be reasonable but other specimens from the latest horizons would have to be discovered to confirm this hypothesis.

- Hypothesis 4 considers *M. subapenninum* as monomorphic species (it gradually evolved from “female” to “male” morphotypes). This hypothesis holds that the “female” morphotypes should be present only (or predominantly) in the earliest horizons, and the “male” morphotypes should be present only (or predominantly) in the latest horizons. The authors also consider that an individual variation might have existed in an intermediate stage. In this case the hypothesis could be possible because the earliest horizons contain the “female” morphotypes, whereas the latest ones contain the “male” morphotypes. Moreover MGGC 9160 could represent the intermediate condition. This scenario could be plausible, but the available data can not presently confirm it with certainty.

- Hypothesis 5 is related to the degenerating monomorphism of *M. subapenninum*: the species is primarily monomorphic, but later it became sexually dimorphic. The earlier horizons should contain predominantly the “male” morphotypes, whereas the latest ones should be comprised of both morphotypes in equal proportions. The available data do not support this hypothesis because no “ male” morphotype is known in the earliest horizons.

The authors conclude that the hypothesis 3 and 4 are the most plausible and that sexual dimorphism in *M. subapenninum* can not be demonstrated by the existing data.

On the basis of these considerations, the recent discoveries in the Arcille area, and in particular the presence of two tusked specimens (MSNTUP I 15892 and GAMPS 62 M) can further support to hypothesis 3 and 4. In fact both specimens show the "female" morphotype, and furthermore they were discovered in the earliest horizons: two necessary conditions for supporting these two hypotheses (Fig. 3.6).

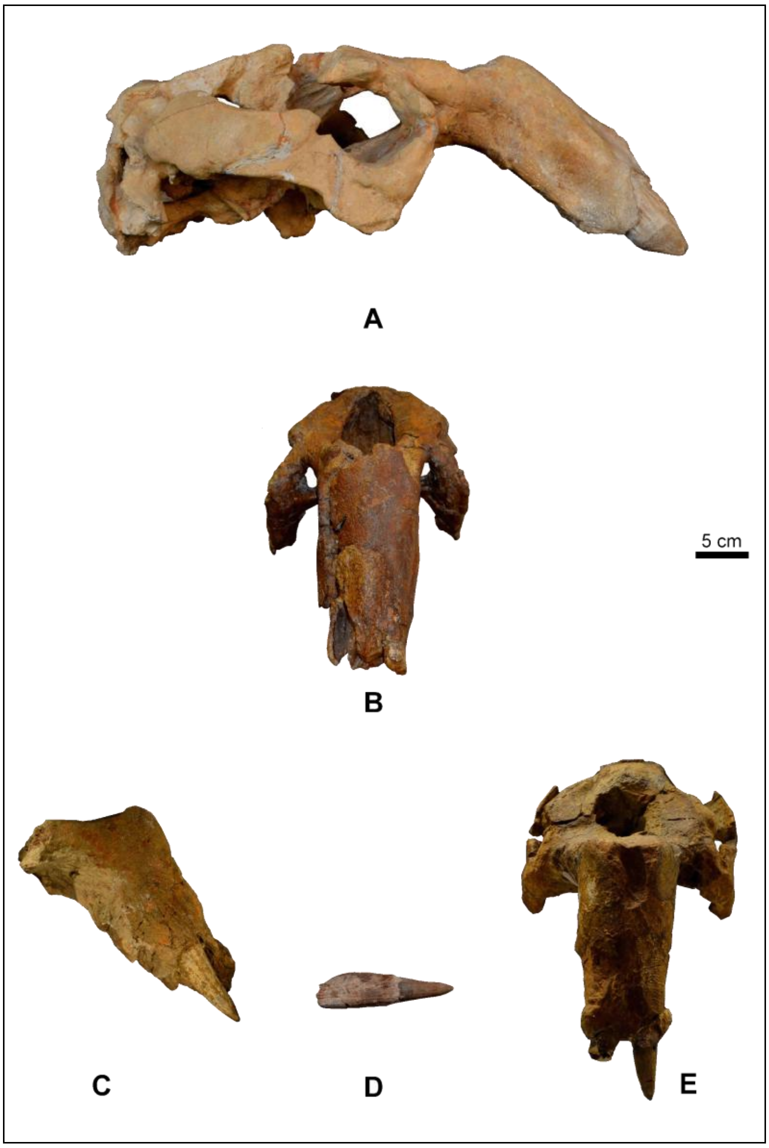

Fig. 3.6 Comparison between some *M. subapenninum* tusks: A) Bra specimen, "male" morphotype; C) MGGC 9160, an intermedie condition between "male" and "female" morphotypes; C) D) E) MSNTUP I 15892, GAMPS 62 M and IGPS 13747, "female" morphotype.

With regard to post-cranial skeleton, some considerations can be made on the scapula and humerus of MSNTUP I15892.

In addition to the right scapula of MSNTUP I15892, only a left scapula (MGGC 9160) (Fig. 3.7) and a fragment of the right scapula (IGPS 223) are known. Comparing the two most complete specimens (MSNTUP I15892 and MGGC 9160), the scapulae appear to be very similar even if the right scapula of MSNTUP 15892 is smaller than that of MGGC 9160. The neck appears to be narrower in MGGC 9160 than in MSNTUP 15892; in dorsal view, the scapula of MSNTUP I15892 has the posterior and anterior borders more concave than those of MGGC 9160. Furthermore, the supraglenoid tuber is more developed in MSNTUP I15892 than in MGCC 9160.

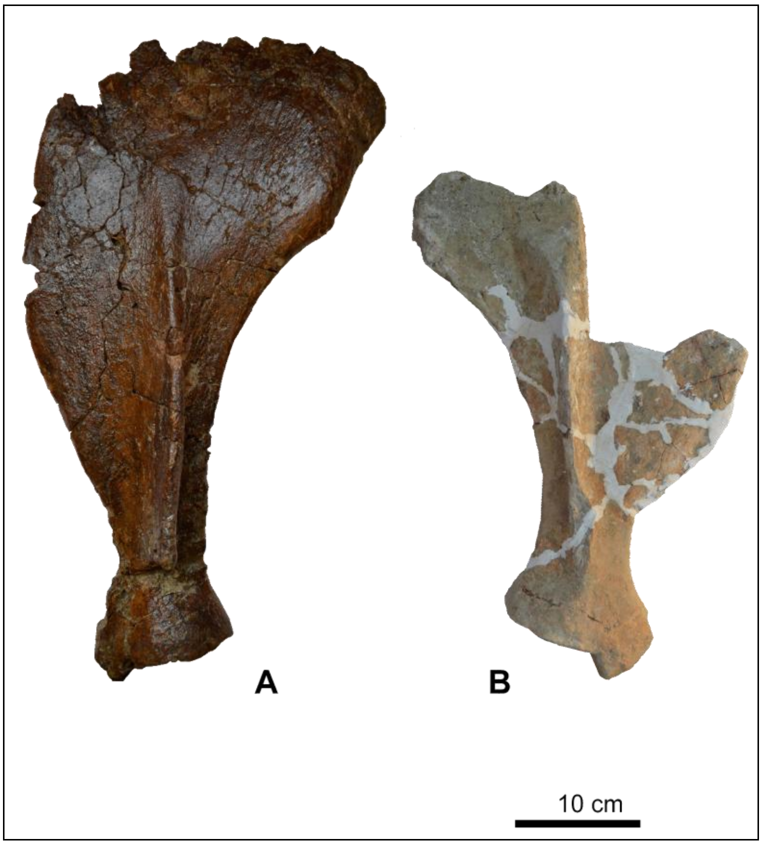

Fig. 3.7 Comparison between the left scapula of MGGC 9160 (A) and the left scapula of MSNTUP I15892 (B)

The left humerus of MSNTUP I 15892 was compared with an almost complete left humerus (IGF 8743V is been referred by Sorbi and Vaiani, 2007 to *Metaxytherium* cf. *subapenninum*) (Fig. 3.8).

A right humerus housed in the Museo Paleontologico dell'Università degli Studi di Genova (DSTG 2519/Ge-IV-G 13) is badly preserved and it is only represented by the distal portion. The humerus of MSNTUP I15892 is smaller and less slender than the humerus of IGP 8743V, even if the general morphology of this latter one could be affected due to its state of conservation (it appears to be heavily damaged by erosion). The maximum length (from the grater tubercle to distal end) is 163 mm in MSNTUP I 15892, whereas it is 242 mm in IGF 8743V. Also the maximum breadth (from greater to lesser tubercle) is slightly different between the two specimens: in MSNTUP I 15892 it is 86 mm and in IGF 8743 is about 108 mm.

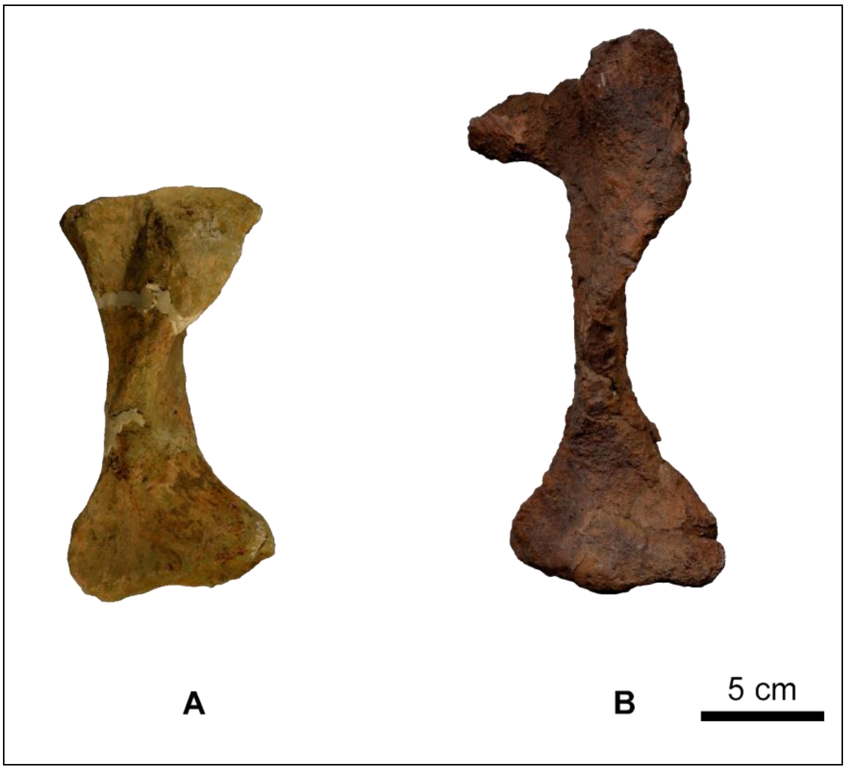

Fig. 3.8 Comparison between the left humerus of MSTUPI I15892 (A) and the left humerus of IGF 8743V (B)

With regard to the vertebral column, and in particular to the morphology of vertebrae, no substantial difference was observed between MSNTUP I 15892 and the other *Metaxytherium* specimens.

Finally, MSNTUP I 15892 does not substantially differ in any characters from the other *M. subapenninum* specimens, and the few differences previously described are substantially due to its young age.

Chapter 4

GEORADAR AND PALAEONTOLOGY

4.1 NTRODUCTION

Fossil vertebrates are often concentrated in peculiar fossiliferous layers exposed in a relative narrow areas. The field research for these fossils is often conducted randomly and the process might entail a considerable amount of time and funds. In fact, most of fossils may be covered by sediments and it is necessary to do intensive excavation to recover them and to evaluate their effective extension.

Moreover the fossiliferous sites can be localized in areas interested by anthropogenic activities, as quarries, cultivate fields and building constructions. In these cases the time required to find fossils can be even more onerous and the palaeontological field research might hinder or completely stop the anthropogenic activities. Unfortunately, whenever the field research cannot be conducted, the fossils are often partially o totally destroyed by the ongoing activities.

In this context, the Ground Penetrating Radar (GPR) technique may be successfully used to detect fossil vertebrate remains, optimizing the palaeontological fieldwork, reducing excavation times and providing a benefit for the local planning.

The GPR technique has been long applied in civil engineering, geological, environmental, forensic and archaeological contexts (Joel, 2009). However, its use in vertebrate palaeontology is very rare[1]; in fact, there are few examples relating to this scientific research: the first known GPR palaeontology field tests were conducted by Bernhardt et

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[1] Other two applications of this geophysical method in vertebrate palaeontology have been recently carried out by the some authors of recently published work (Tinelli et al., 2012). These applications have been performed in two sites: Val D'Orlo locality (Castelfiorentino, Firenze, Italy) and Lucciolabella locality (Pienza, Siena, Italy). The unpublished data have allowed to confirm the success of georadar technique for the investigation of fossil vertebrates.

al., 1988 and Borselli et al., 1988. In both cases, GPR was applied in different geological contexts: Bernhardt et al., 1988 considered both the fluvial-lacustrine clays of Rotonda (Potenza, Italy) where some terrestrial vertebrates were discovered, and some of the “Pietra Leccese” rock blocks in which some vertebrate remains (fish, reptiles and mammals) were found, while Borselli et al., 1988 referred to a fossiliferous mammalian deposit in the Pleistocene lacustrine sediments at Colfiorito (Perugia, Italy). In both cases, the results were satisfactory and encouraging. Carrozzo et al., 2003 described the use of GPR to verify its resolution to locate some vertebrate remains within three biomicrite samples in which the position of fossils was known. The test was performed considering different varieties of “Pietra Leccese” and, although the response of methodology was very different in the three cases, the success of this application was confirmed.

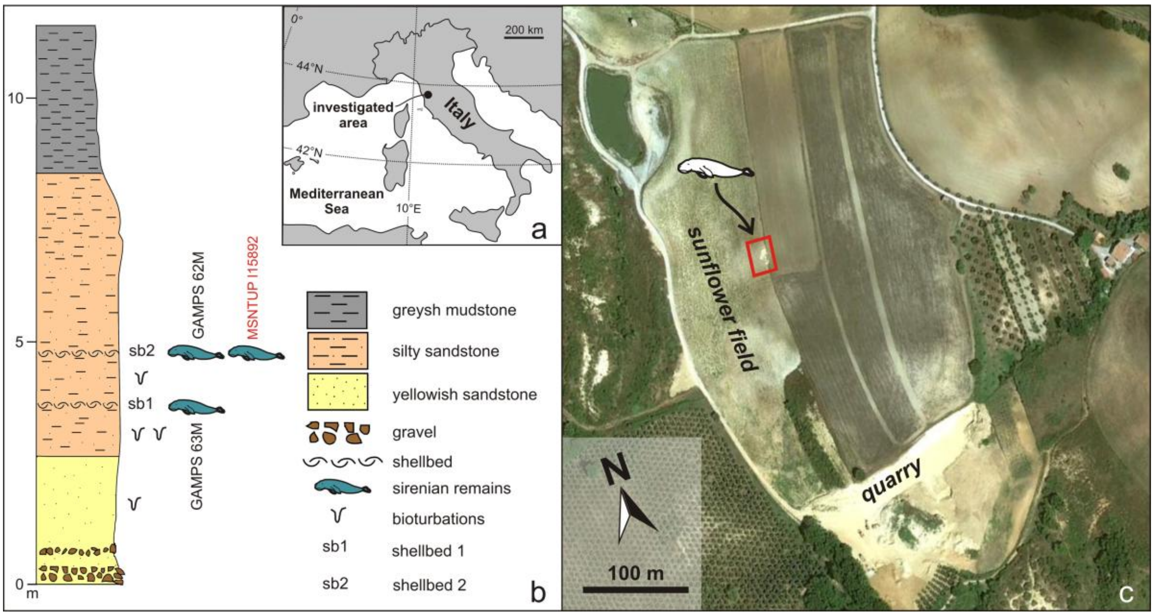

Fig. 4.1 a, Location of the investigated area; b, Schematic stratigraphic succession of the Early Pliocene sediments from the Arcille area (Grosseto, Tuscany); c, Location of the specimen MSNTUP I15892 in the sunflower field, discovered by using Ground Penetrating Radar (GPR).

Other studies about the application of GPR to palaeontology were conducted by different authors, especially considering dinosaurs sites (e.g. Gardner and Taylor, 1994; Gillette, 1992, 1994a,b; Main and Hammon, 2003; Meglich, 2000; Schwartz, 1994). Some results are actually positive: for example, Main and Hammon, 2003 conducted the GPR surveys in two sauropod quarries in the Lower and Upper Cretaceous rocks of Texas. They concluded that the GPR technique was a key tool to locate buried fossils that could hardly be detected using the traditional methods. Both Gillette, 1994b and Schwartz, 1994 referred to the GPR surveys in a sauropod site in New Mexico, but they reported the failure of this application. Finally Gardner and Taylor, 1994 described the application of GPR to the Bone Cabin Quarry in the Morrison Formation of Wyoming, but they did not confirm the GPR data. Meglich, 2000 reached the same conclusion using GPR technique in a dinosaur site in Colorado.

The potential of this application to vertebrate palaeontology may be increased if more tests are conducted in different geological and palaeontological context. Although this region is one of the most important sites in Italian Pliocene record of marine mammals (e.g. Bianucci, 1996; Bianucci and Landini, 1999; Bianucci and Landini, 2005; Bianucci et al., 1998, 2001, 2009; Bisconti, 2002; Capellini, 1902, 1904, 1905; Fondi and Pacini, 1974; Lawley, 1876; Pilleri, 1987; Sorbi and Vaiani, 2007; Tavani, 1942a,b; Ugolini, 1900a,b, 1902, 1907), geophysical surveys were never used to support palaeontological research.

This study presents a first contribution relating to a GPR application to detect a skeleton belonging to a fossil sea cow (Mammalia: Sirenia), recently discovered in a lower Pliocene deposits outcropping near Grosseto (Tuscany, Italy).

Considering that the skeletal structure of these mammals is very dense and massive, the fossiliferous sediments are relatively homogeneous, tectonic disturbs in the investigated area are absent, the depth of fossil skeleton from the surface is low and the field surface have a regular morphology, it is possible that these factors represent optimal conditions for this type of investigation.

4.2 THE PALAEONTOLOGICAL SITE

The lower Pliocene fossiliferous layer where the fossil sirenian was found is exposed in a small area near Arcille (Grosseto, Italy) (Fig.4.1a). The succession outcropping in this area consists of shallow marine siliciclastic deposits. They contain a planktonic foraminiferal assemblage consistent with their attribution to the lower part of the Zanclean, in particular to the MPl2 zone of Cita, 1975, dated between 5.08 and 4.52 Ma (age after Lourens et al., 2004). The succession, affected by systems of normal faults, is dominated by yellowish, locally pebbly, fossiliferous sandstone overlain by greysh mudstone (Tinelli et al., 2011).

Three partially articulated sirenian fossil skeletons were found in 2007 in a sand quarry located in this area and they are now kept in the museum of the Gruppo Avis Mineralogia e Paleontologia di Scandicci (GAMPS) near Florence. Their catalogue numbers are GAMPS 62M, GAMPS 63M and GAMPS 64M.

All specimens belong to *Metaxytherium subapenninum*, a halitheriine dugongid (Mammalia: Sirenia) that lived in the Mediterranean Basin and became extinct in the upper part of the Pliocene because of the progressive climatic cooling occurred after 3.1 Ma (Sorbi et al., 2008, 2012).

The discovery of these three sirenian skeletons is a consequence of an excavation activity in the quarry, during which fossil bones were exposed. Unfortunately this activity also caused the partial destruction of the fossils.

Two of them (GAMPS 62M and GAMPS 63M) were found in the upper part of succession, in proximity of two shell beds (sb1 and sb2, see Fig. 4.1b), including fragmented and decalcified shells of bivalves, rare gastropods and scaphopods. GAMPS 62M consists of a partial skeleton composed of an incomplete skull and mandible, some teeth, several vertebrae, ribs and sternum; GAMPS 63M is more fragmentary and composed of teeth, ribs and vertebrae. The third specimen (GAMPS 64M), represented by few ribs and vertebrae, came from sandstone beds whose correlation with the succession containing the other sirenians is unclear.

The fourth specimen, that is the main object of this study, also belonging to *Metaxytherium subapenninum*, was discovered in 2010 in a sunflower field crop few ten meters NW of the quarry (Fig. 4.1c) in the upper part of succession in proximity of sb2 (Fig. 4.1b). During a palaeontological prospection, several fossil bones (mostly fragmented ribs) on the field surface particularly concentrated in a small area near a draw has been observed. Considering the morphology of the field, these bones have not suffered any main displacement but they were put on the surface during the plowing of the field.

This hypothesis was supported by the previous discovery of the three sirenian specimen in the quarry: all of them were represented by more or less complete single skeletons, while no accumulation of bones from different individuals or isolated sirenian bones were collected.

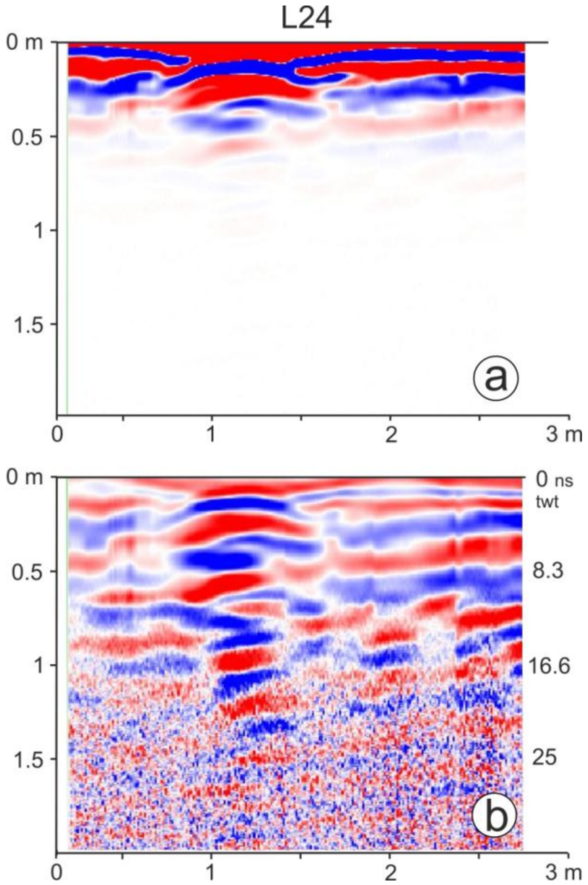

Fig. 4.2 a, processed GPR data with the time-zero correction, and the application of "dewow" and vertical band-pass filters; b, final processed GPR data with the application of gain functions. Twt: two-way traveltime (time taken by the EM to reach the target and to reflect back to the receiver.

Therefore this small area of the sunflower field was considered particularly suitable to test the GPR technique. The specimen is now kept in the Museo di Storia Naturale e del Territorio, Università di Pisa (MSNTUP) and its catalogue number is MSNTUP I15892.

4.3 MATERIALS AND METHODS

GPR method

Since Ground Penetrating Radar is based on the propagation and reflection of electromagnetic (EM) waves, it is sensitive to variations of the EM parameters in the subsoil, especially the dielectric constant and electric conductivity (Davis and Annan, 1989). The lower the frequency of EM waves propagating into the subsurface, the greater their penetration. The latter varies from a few meters in conductive materials to tens of metres for low conductivity media (Annan, 2009; Davis and Annan, 1989; Smith and Jol, 1995). The capability to resolve targets vertically (vertical resolution) increases with the antenna frequency up to centimetre values (> 200 MHz), while it is strongly reduced (several decimetres) when a < 100 MHz antenna is adopted. Lateral resolution depends also on the geometry of acquisition (step size, e.g. the distance between each point where a measurement is made along a GPR profile) and can reach a sub-centimetric resolution. The Nyquist sampling interval, e.g. one-quarter of the wavelength in the ground, is the base value to which the step size of the acquisition refers in order to avoid spatial aliasing effects (Annan, 2009; Davis and Annan, 1989;). Despite its relatively low penetration depth (especially in conductive materials), GPR high resolution (lateral and vertical) makes this technique successful in studies of shallow stratigraphy, structural geology and archaeology (Basile et al., 2000; Bini et al., 2010; Grandjean and Gourry, 1996; Grasmueck, 1996; Grasmueck et al., 2004; Leckebush, 2003; Leucci, 2006; Orlando, 2007; Soldovieri and Orlando, 2009).

Further significant advantages are reached by adopting a grid of radar profiles, allowing a psuedo-3D or full-3D visualisation of the subsurface, and facilitating the interpretation of geometric structures, such as joints pattern, geological contacts and archaeological remains (Malagodi et al., 1996; Nuzzo et al., 2002). In this respect, ‘time slice’ (or depth slice) maps are used to display the plan pattern of radar data at variable depths (Goodman et al., 1995).

In this study, the GPR survey has been performed using the Radar System device of IDS Company © (www.ids-spa.it), equipped with a monostatic antenna of 200 MHz of nominal peak frequency and HH-polarised. The choose of this antenna frequency was guided by the necessity to investigate, at a resolution of some centimetres, a fossil remain located presumably in the first 1.5 m of subsurface.

The data were acquired in continuous mode, controlling the step size by means of an odometer wheel. In vertical direction, the subsurface was explored for 75 ns (range), taking 1024 samples per scan, while horizontally the radar source was triggered every 1.2 cm.

A 0.2 m grid of acquisition was used to cover two sectors centred on a point where bone fragments on the surface suggested the existence of fossil remains beneath.

The following steps describe the sequence of processing applied to the raw radar data:

- Time-zero correction shifting the radar traces by the time of the first reflection of the ground wave;
- Running average filter in order to filter the DC component (Dewow filter);
- Subtracting the mean trace in order to filter out the continuous flat reflections caused by the breakthrough among the shielded antennae and by multiple reflections between the antenna and the ground surface (Daniels, 2004);
- Linear and smoothed gain with window-length of 71 ns (up 3 m depth);
- Vertical band-pass filter;
- Determination of EM wave velocity for depth conversion using the method of hyperbolic shape of a reflection from a point source (diffraction hyperbola).

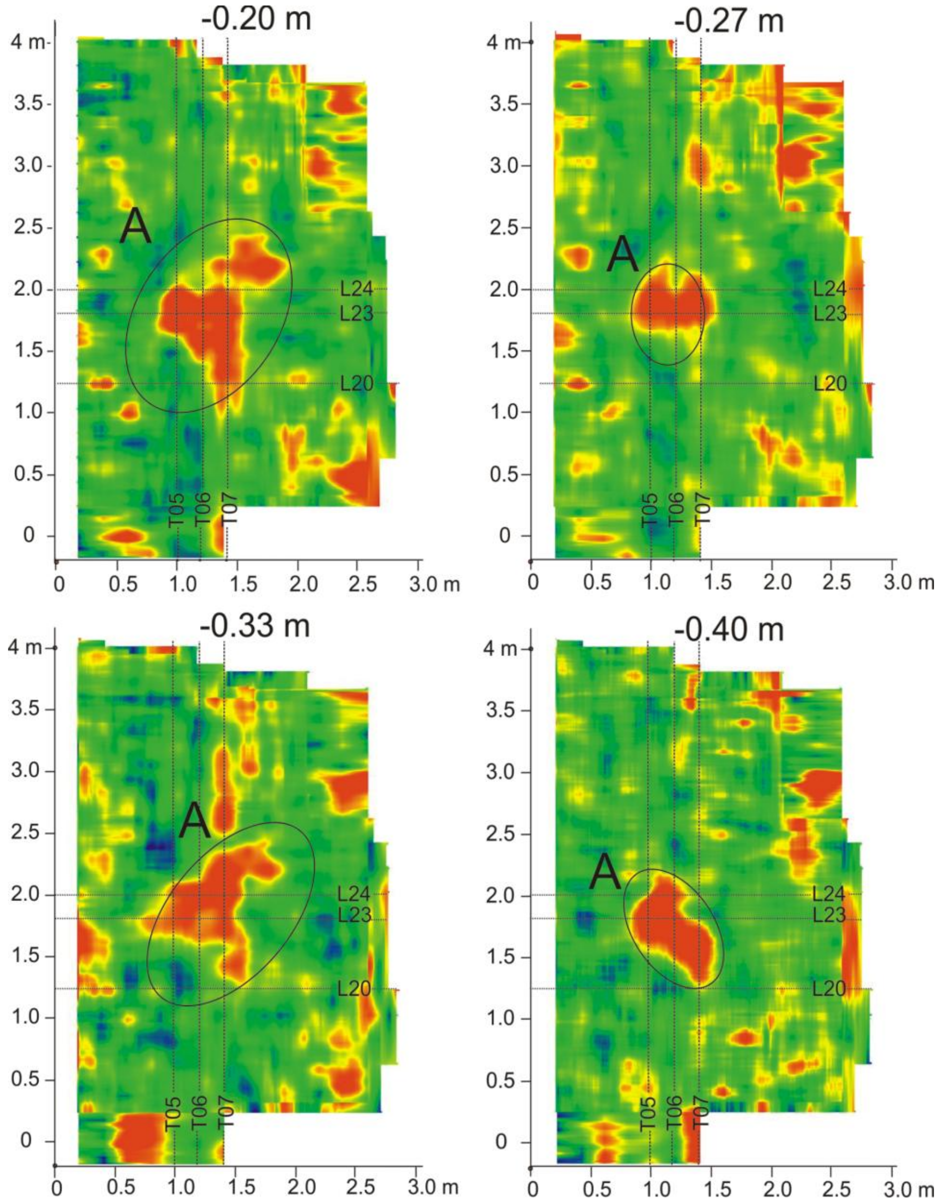

Fig. 4.3 Depth-slices of the GPR data volume (C-Scan) in the Area 1. In red, the most reflective zones. A indicates the reflective zone corresponding to the principal fossil remains. The traces of the vertical radar profiles reported are indicated.

- *Palaeontological method*

In order to compare GPR map and the location of fossil remains, a grid system has been realized: it is formed by squares (0.40 m x 0.40 m) where the relative position of each bones was recorded using an alphanumeric code for each square, as showed in Fig. 4.6.

The excavation of the sirenian remains was conducted following the standard procedure for macrovertebrate collecting (Borselli and Cozzini, 1992; Greenwald, 1989; Leiggi et al., 1994). Firstly all bones were partially exposed on the surface and strengthened with a reversible polyvinyl acetate consolidant, then the blocks of sediment containing one or more associated bones were partially isolated from the surrounding rock digging trenches around them. Once a fossiliferous block was isolated, fossil bones were covered with a layer of wet paper towels. Burlap strips soaked with plaster were placed one at a time on the block. After the plaster was hardened the block was undercut and completely separated from the surrounding rock. To collect the largest block (2.0 x 2.0 x 0.5 m), containing most of the sirenian bones, a steel-and-wood frame has been made and the plaster-jacketed block has been covered with polyurethane. Finally, this large block was transported to the museum by grab truck.

4.4 RESULTS

GPR survey and analysis

GPR method was used in two adjacent areas (Area 1 and Area 2) of the sunflower field (Figs. 2-6), both covered with survey lines 0.2 m apart. In the vertical direction, the subsurface was explored for 60 ns (range) which corresponds to 3 m considering a wave velocity of 10 cm/ns. For each registration 1024 samples were taken, while horizontally the radar source was triggered every 1.2 cm (step size). These sampling frequencies have been considered appropriate to reconstruct vertically and horizontally the reflection pattern in the subsurface, avoiding spatial aliasing. The following steps describe the sequence of processing applied to the raw radar data.

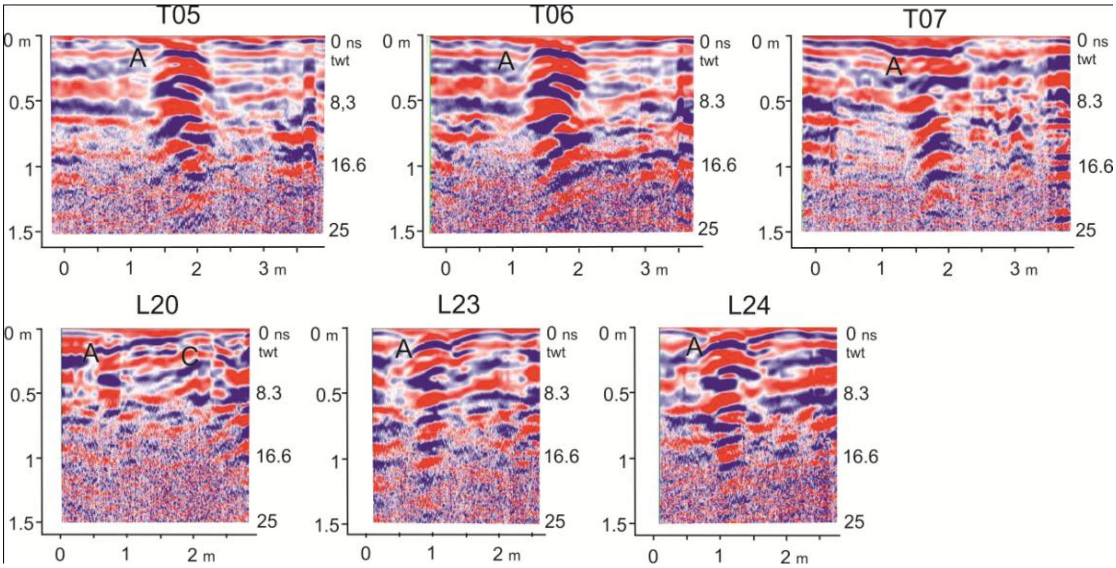

Fig. 4.4 Selected vertical radar profiles (B-scans) the Area 1. A indicates the reflective zone corresponding to the principal fossil remains. The code indicates the number of the profile. For profile location, see Fig. 4.3.

The radar acquisition in each measurement point was shifted by the time of the first reflection of the ground interface, adjusting traces to a common time-zero position (time-zero correction).

To remove the saturation effect caused by the EM wave travelling in air ("wow"), a running average filter was applied (Dewow filter). A mean trace was subtracted to filter out continuous flat reflections caused by the breakthrough among the shielded antennae and by multiple reflections between the antenna and the ground surface (Daniels, 2004). Following a spectral analysis of measured signals, a vertical band-pass filter (160-800 MHz) was applied to the data in order to remove undesired frequency components coming from instrumental and environmental noises. A first view of the results after these processing steps is reported in Fig. 4.2a. To enhance the visibility of deeper reflections due to signal attenuation, gain functions were applied to the data. Specifically, linear gain function (increasing with depth) and smoothed gain function with window-lengths of 2 ns were adopted. To convert the radargram from time to depth domain, an estimate of the average subsurface EM wave velocity is needed. The method of hyperbolic shape of a reflection from a point source (diffraction hyperbola) for this estimation was adopted. To estimate EM velocity, a velocity specified-hyperbolic function to the form of a diffraction hyperbola detected in the radargram (Cassidy, 2009) was matched. This operation was repeated in some radargrams to obtain an average velocity of 12 cm/ns, eventually applied to the rest of the data to convert depth in time value. An example of final processed data and velocity determination is reported in Fig. 4.2b. Time slice sections were generated using the amplitude of reflections recorded by the receiving antenna. The amplitudes recorded along the survey line were interpolated with those recorded along the adjacent lines in a time windows of 0.8 ns, generating 2D images of reflections pattern at selected depths.

After the sequence of data processing described above, time slices at various depths in Area 1 indicated the presence of a large irregular reflective zone (A) approximately in the centre of the area (Fig. 4.3). This zone is persistently irregular in shape, appears at about 0.20 m in depth and shows a progressive size decrease in depth. The inlines and crosslines radar profiles crossing this zone coherently highlight strong reflections starting at about 0.2 m in depth and propagating to more than 1 m in depth. The reflections are mostly hyperbolically shaped (e.g. T05 and T06), locally overlain by flat horizons, gently concave upward (e.g. T07) (Fig. 4.4). At the right upper corner of Area 1, some minor zones of high back scattered energy appear. Here the presence of a small scarp did not allow to perform the crosslines acquisition, resulting in a distortion in the time-slice generation.

In Area 2 a grid was used and it is formed by 15 transvers lines and 46 longitudinal lines, placed to generate an acquisition area matching the adjacent Area 1 (Fig. 4.5). Just a few bone fragments were found on the surface of this area. A reflective zone was recorded at

0.5-2.5 m of coordinates (B), and results persistent up to 0.5 m depth showing a globular to pseudo-rectangular shape. A second zone with high reflection energy was placed at 2.3-4.8 m (C) and it is evident up to 0.5 m.

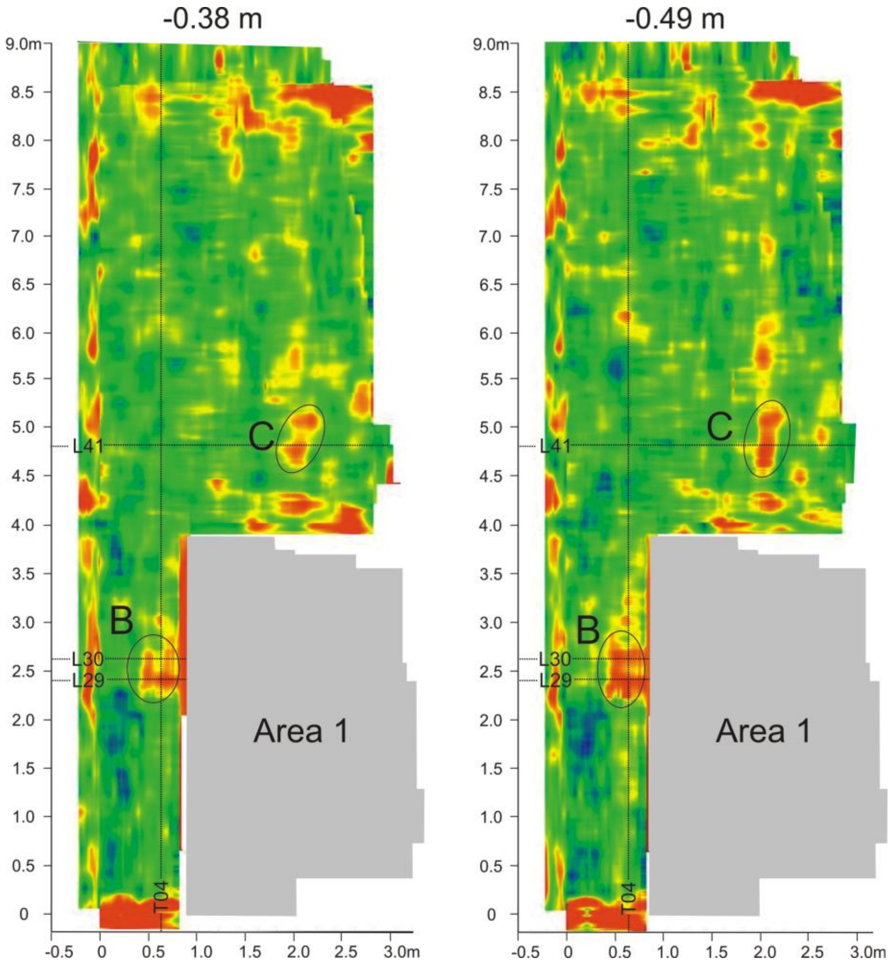

Fig. 4.5 Depth-slices of the GPR data volume (C-Scan) in the Area 2. In red, the most reflective zones. Letters indicate the reflective zones discussed in the text. The traces of the vertical radar profiles reported on the figure are indicated.

Radar profiles crossing these zones do not show evident reflections, likely in part convoluted in the reflections of horizontal discontinuities in the subsurface. In detail, the B zone corresponds to a part of the radar profile characterised by flat reflectors of high back scattered EM energy. C zone lies in correspondence of an energetic reflector below

0.3 m of weak and disturbed signal (Fig. 4.6). In both cases these zones do not present a distinct shape as compared to others reflectors in the radar profiles.

Palaeontological data

Following up the obtained GPR results, these signals have been verified through an excavation extended to the whole investigated surface for Area 1 and in correspondence with the reflective zones for Area 2. For additional verification of GPR mapping process, the GPR map with the map of skeletal elements reported in the grid system (Fig.4.7a,b) were compared.

In correspondence with the central reflective zone (A) of Area 1, some fossil bones emerged: in particular, a skull with tusks at a depth of 0.20-0.25 m, a mandible and several ribs (in D4, D5, D6 and E6) at a depth of 0.26-0.30 m; an axis, one dorsal vertebra and a considerable number of ribs (in E3-4 and F3-4) at a depth of 0.31-0.36 m; and an atlas, an undetermined bone (between D3 and E3) and some fragmented ribs (in E5 and F5) at 0.36-0.40 m in depth.

A Humerus, a cervical vertebra, a scapula and other fragmented bones were found nearby the skeleton: the cervical vertebra at a depth of about 0.26-0.30 m and the humerus at a depth of about 0.31-0.35 m. The scapula and the fragmented bones - the furthest from the skeleton- were 0.36-0.40 m in depth. Neither the cervical vertebra and humerus nor the scapula and other bones were in correspondence with the central reflective zone. The comparison between the GPR map and the distribution of skeletal elements in the grid system revealed that these bones were found near the border of the area where some minor zones of high back scattered energy appear. These reflective zones can be ascribed to environmental noises generated by out of line reflections or ploughed soil by the agricultural activity. At the transition between the two areas, some fragmented caudal vertebrae at the depth of 0.4 m (they are not reported in Fig. 4.7a) were discovered. The lateral position and the depth of these bones could be compatible with those of the reflective zone B of the Area 2, but it is not possible to confirm this correspondence, also because some flat reflectors of high back scattered energy are located near the B zone (Fig. 4.5).

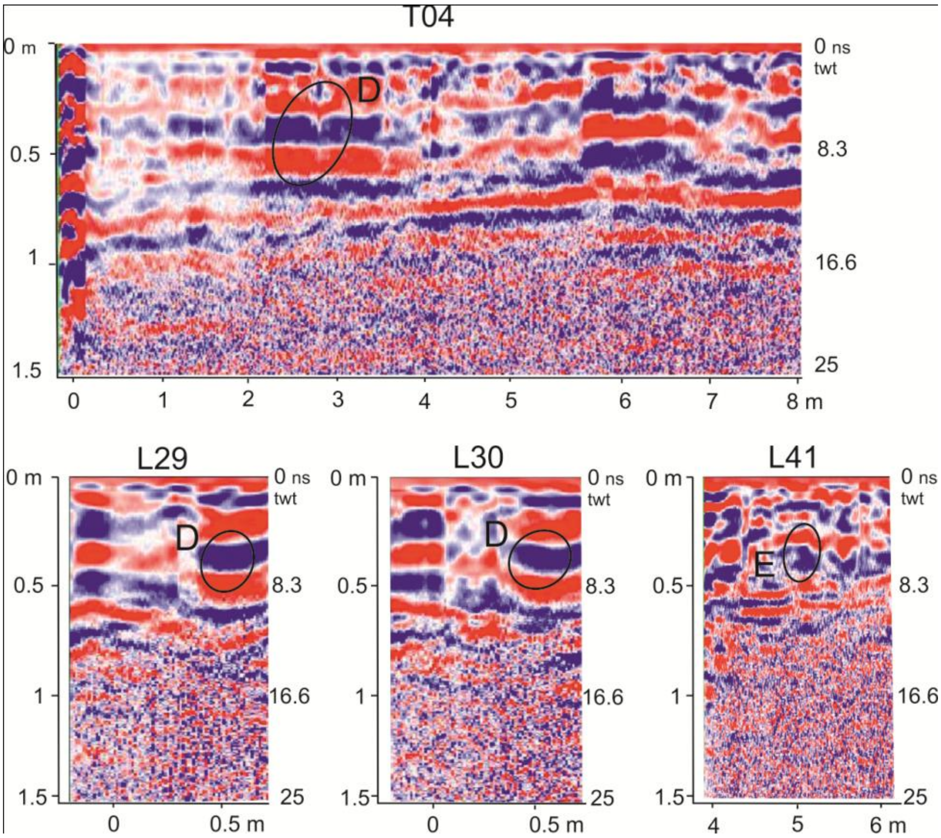

Fig. 4.6 Selected vertical radar profiles (B-scans) the Area 2. Letters indicates the reflective zones discussed in the text. The code indicates the number of the profile. For profile location, see Fig. 4.4.

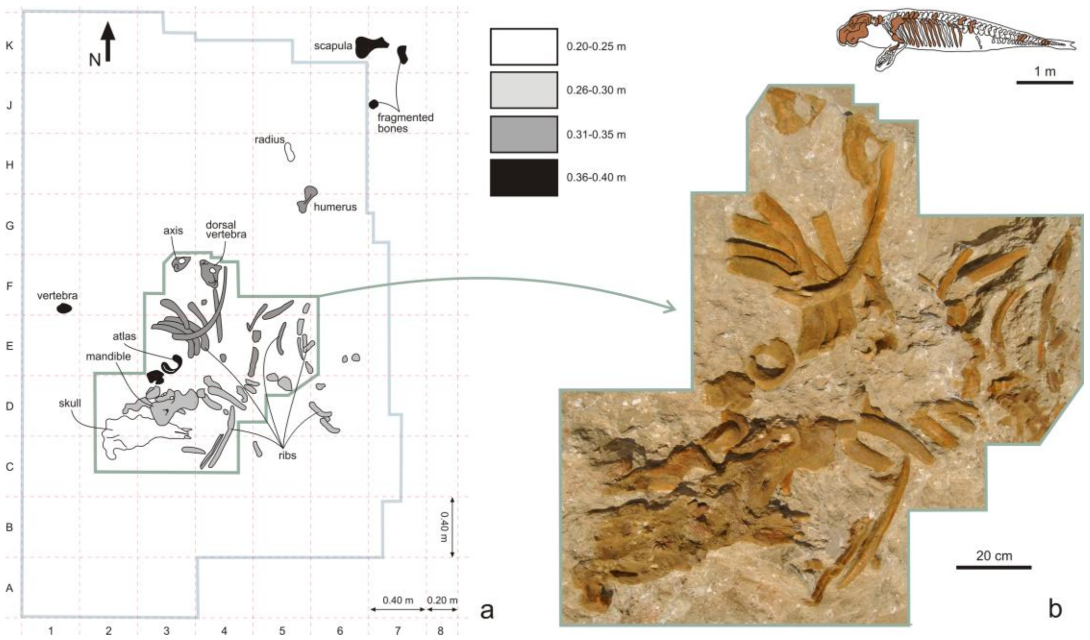

Fig. 4.7 a: grid system reporting all the bones discovered during the excavation and the range of depths at which each bone was found (the largest polygon indicates Area 1); b: detail of the area with bone concentration. The skeleton at the top right highlights the discovered bones.

No fossil remains emerged where the second reflective zone C of Area 2 was localized. Only a concretionary level that might have generated the reflection was observed.

4.5 DISCUSSION AND CONCLUSIONS

The GPR prospection undertaken near the out cropping of several fossil bones on the field surface indicated the presence of reflective zones in the subsurface at various depths. The excavation confirmed that these zones were mostly corresponding to buried bones. In order to compare reflectors and fossil remains in the subsurface, during the excavation each fossil bone has been mapped using a grid system. By comparing geophysical and palaeontological data, the effectiveness of GPR for detecting fossil bones was verified, with clear reflections corresponding to the skull, the mandibles, some cervical and dorsal vertebrae and ribs.

However, some reflections were not generated by fossil remains. These types of reflections are mostly related to a concretionary level in the silty sands or soil clumps locally associated to voids caused by agricultural activity.

In other cases, fossil remains either did not reflect back electromagnetic energy, or the shape of the backscattered energy is not fully consistent with the shape of the fossil assemblage. Heterogeneous bone density and GPR vertical resolution may be the explanation of these missed or partial targets. In general sirenians have heavy skeletons that help them to stay submerged. Sirenian bones are both swollen (pachyostotic) and dense (osteosclerotic), especially the ribs, which are often found as fossils (Domning, 2002). The central reflective zone (A) is in correspondence to a high concentration of ribs, therefore it can be due to their massive and dense structure, a GPR antenna could very easily detect the sirenian ribs. However, laboratory experiments to determine EM characteristics (mainly electric permittivity) of different types of bones are needed to support this hypothesis. Vertical GPR resolution (e.g. the minimum vertical distance between two objects in the subsurface to be distinguished with two separate reflections) is assumed to be 1/4 of the signal wavelength (λ). In this case, this means that bones vertically spaced of less than 0.12-0.13 m may be represented by a single reflection instead two distinct events in the radargram. Hence, the missed reflections of some undetected bones may have been convoluted in the reflective event of shallower objects.

In order to overcame this problem, a higher frequency antenna should be used, provided that the fossil remains are assumed to be found at a very shallow depth (< 1.0-1.5 m), thus avoiding the loss of signal caused by the EM wave attenuation with depth.

Based on all considerations above stated, it is possible to conclude that GPR surveys, as applied to palaeontological field research, turned out to be a time-cost effective solution and a tool for the local planning. Despite the encouraging results, in order to refine this application in vertebrate palaeontology it is necassary that further experimentations need to be conducted in different geological and palaeontological contexts and with higher frequency antennae (> 200 MHz), especially when it is presumable that fossil remains lie at shallow depths.

However, considering that geophysical technologies and techniques evolve continuously, it is clear that much more testing will have to be conducted to further improve the use of this methodology in vertebrate palaeontology.

Chapter 5

GENERAL CONCLUSIONS

The first part of the study concerned the geological, stratigraphical and taphonomic analyses carried out in four sedimentary successions of southern Tuscany. In particular the Arcille, Camigliano (CAM), Poggio alle Mura (PAM) and Monte Antico (MA) successions have been studied in details. These successions crops out in the south-west (Arcille succession) and north-east (CAM, PAM and MA successions) area of Baccinello-Cinigiano Basin, a Neogene post-collisional basin (Martini and Sagri, 1993). The study on these sedimentary successions highlighted some interesting stratigraphical, palaeoenvironmental and taphonomic analogies. In fact, both in Arcille succession and CAM, PAM and MA successions have been recognized a general transgressive trend. The regressive portions are represented by pebbly sandstone and older delta-front sediments in Arcille succession and unstratified matrix-supported conglomerates in MA and PAM successions, deposited during periods of relative falling of sea level. The marine transgression starts with the deposition of fossiliferous bioturbated massive sandstones and it culminates with the massive greyish mudstones. One of the most important aspect observed in these successions is the presence of a laterally continuous shell-bonebeds ast the transition between sandstones and mudstones. These shell-bonebeds, described in detail in chapter 2, are generally characterized by a high mollusc and vertebrate concentration. Molluscs are found in different states of preservation (poorly ordered rounded convex-up and convex-down valves, sandy-filled internal moulds, disarticulated shells) and they are characterized by an elevate number of taxa (only in few cases they were determined at the level of species). Other invertebrate remains are also found in these layers. The vertebrate concentration is extraordinarily high: in Arcille successions three incomplete sirenian skeletons have been found in correspondence of shell-beds: all these specimens have been referred to *Metaxytherium subapenninum* (see chapter 3). The taphonomic study led to observe that all sirenian skeleton are characterized by a similar preservation pattern: all sirenian bones are disarticulated, but closely associated. A description of the state of bone preservation is reported in detail in chapter 2. In the PAM and CAM successions a nearly complete skeleton of a Mysticete, an incomplete left humerus of *Metaxytherium* cf. *subapenninum* (Sorbi and Vaiani, 2007) and some articulated vertebrae of an Odontocete have been found in correspondence of the laterally continuous shell-bed. The Montalcino whale skeleton is characterized by a similar preservation pattern observed in sirenian skeletons discovered in Arcille area. Whale bones are in fact disarticulated (especially those of the skull), but closely associated. The stratigraphical, taphonomic and palaeoenvironmental analyses carried out in these two area led to the interpretation that the stratigraphic interval including the two shell-beds with marine vertebrates is condensed deposits. In particular this stratigraphical interval marks a period of sedimentary starvation followed by the replacement of an outer shelf setting. Furthermore this study allowed to hypothesize that the shell-bonebeds are genetically linked and that they could correspond to the same episode of sediment starvation. These conclusions are supported by similar sedimentological, stratigraphical, palaeontological and taphonomic features. The results obtained by micropalaeontological analyses also support this hypothesis because both studied successions are assigned to *Globorotalia margaritae* Zone (Cita, 1975; Iaccarino, 1985) dated to 5.08- 4.52 Ma.

The second part of this study concerned the systematic palaeontology. It consisted in the description of four sirenian specimens found in Arcille locality. In particular MSNTUP I 15892 and three GAMPS specimens (these three last specimens have been summarily reported also in Sorbi et al., 2012) represent the object of this study and they are assigned to the *Metaxytherium subapenninum* (Bruno, 1839; Fondi and Pacini, 1974). Almost all *M. subapenninum* specimens found from the beginning of the nine-teenth century are personally examined, whereas the specimens discovered out of Italy have been studied through literature (Sorbi et al., 2012).

MSNTUP I15892 is composed by a nearly complete cranial and post-cranial skeleton and it is a juvenile individual (the first two lower molars are moderately to heavily worn, but m3 is not completely erupted; the epiphyses of humerus is not fused with diaphases) and it is probably a female ("female" morphotype, see Sorbi et al., 2012). The skull is represented by the following bones: premaxilla, nasal, frontal, lacrimal, parietal, supraoccipital, exoccipital, maxilla, squamosal jugal and mandible). The upper cheek teeth are poorly preserved and it is represented by only two incisors (tusks) still fixed in their alveoli. Lower cheek teeth are represented by right dp5 and right and left molars. The post-cranial skeleton is incomplete: the vertebral column is represented by the atlas, axis, a body of cervical vertebra, thoracic and lumbar vertebrae (still encompassed in the matrix) and some caudal vertebrae; a lot of fragmented and almost complete ribs; the left humerus and the right scapula.

GAMPS 62 M is composed by a few isolate badly preserved cranial remains and by mostly well-preserved post-cranial skeleton. It is a young individual because it has an open-rooted tusk. The skull is represented by parietal, supraoccipital, exoccipital, basioccipital, basisphenoid presphenoid, maxilla, squamosal, left periotic, left tympanic and mandible. The upper cheek teeth are represented by an isolated right tusk, right M1, left M2 and left and right M3. The lower dentition is composed by only left m2. The post-cranial skeleton is almost complete: the vertebral column is composed by 16 vertebrae (four posterior-most thoracics, three lumbars, one sacral and eight anterior-most caudals) and a complete anterior chevron bone; there are 11 left ribs and 7 right ribs (in addiction there are also a lot of isolated and fragmented ribs) and an almost complete sternum.

GAMPS 63 M and 64 M are composed by only a few post-cranial remains: the former is represented by seven thoracic vertebrae and a lot of fragmented ribs, whereas the latter is composed by three thoracics and fragmented ribs.

A recent study of morphological features of *M. subapenninum* tusks has been carried out by Sorbi et al., 2012. The discovery of MSNTUP I 15892 and GAMPS 62 M, two tusked specimens, confirms that two hypotheses (3 and 4), reported in Sorbi et al., 2012, are mostly unlike to explain the evolution of dimorphism in *M. subapenninum* tusks. This study also confirms that the sexual dimorphism can not be ascertained.

The third part concerned to the description of the recent discovery of one of the examined sirenian skeleton (MSNTUP I 15892) found in Arcille by using Ground Penetrating Radar. The results of this study have been recently reported in Tinelli et al., 2012. The GPR technique has been long applied in civil engineering, geological, environmental, forensic and archaeological studies (Joel, 2009), but its use in vertebrate palaeontology is very rare. A few examples can be cited in literature (e.g. Bernhardt et al., 1988; Borselli et al., 1988; Gillette, 1992; 1994a;b; Gardner and Taylor, 1994; Main and Hammon, 2003, Meglich, 2000; Schwartz, 1994). Other two applications were also recently performed in Val d’Orlo locality near Castelfiorentino (Florence) and in Lucciolabella locality near Pienza (Siena) by the same authors of the recently published work (Tinelli et al., 2012).

The GPR survey in Arcille locality was performed using the Radar System device of IDS Company, equipped with a monostatic antenna of 200 MHz. Two adjacent areas have been mapped. Time slices at various depths indicated the presence of several reflective zones: one of this was located at the centre of the first area at 0.20 m from surface. The other zones were smaller and not persistent and rapidly changing in shape with depth. In the second area, two small zones were recorded.

To verify the nature of this GPR signals a palaeontological excavation was conducted. Some fossil bones emerged in corrispondance with the central reflective zone of the first area: in particular, the skull with tusks, the mandibles with teeth, some cervical and dorsal vertebrae and a considerable number of ribs. Other bones (humerus, a body of cervical vertebrae and scapula) were found in correspondance with smaller reflective zones of the same area.

In the second area, several caudal vertebrae in correspondence of one of the two reflective zones were discovered.

The results obtained from this study are very interesting and encourage further applications, that are required for a further refinement of this surveying method for palaeontological research.

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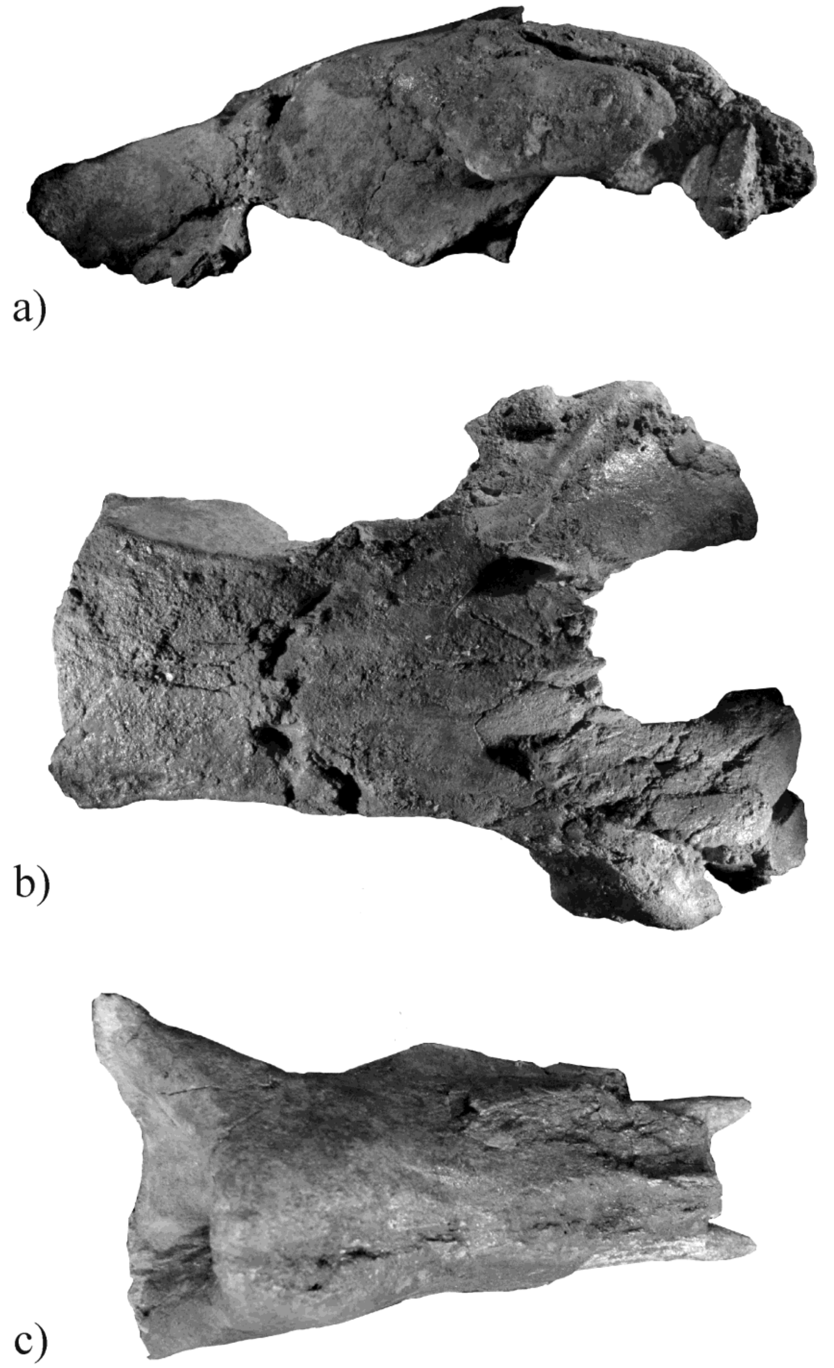
ANATOMICAL PLATES

PLATE 1



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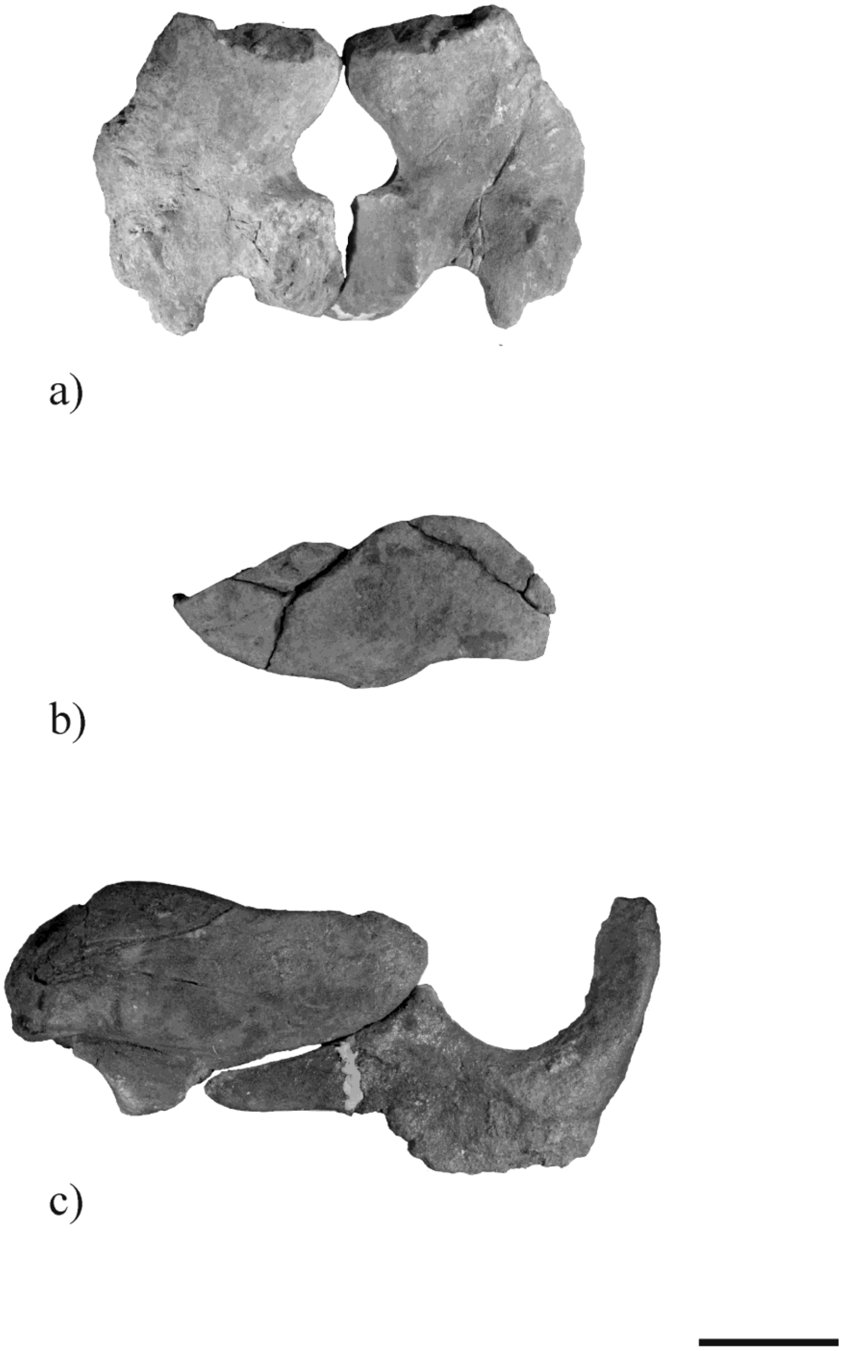


PLATE 3

a)

b)

PLATE 4

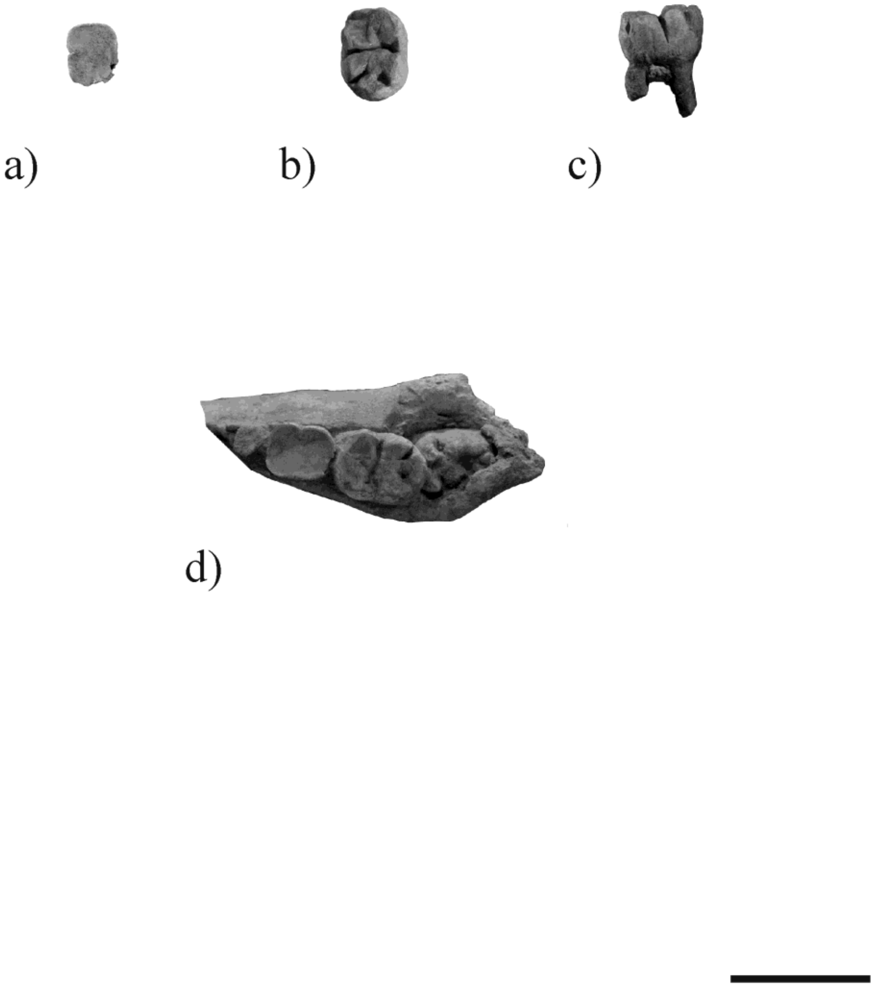
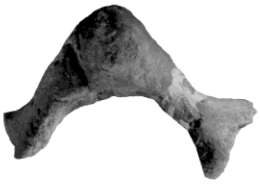


PLATE 5

a)

b)

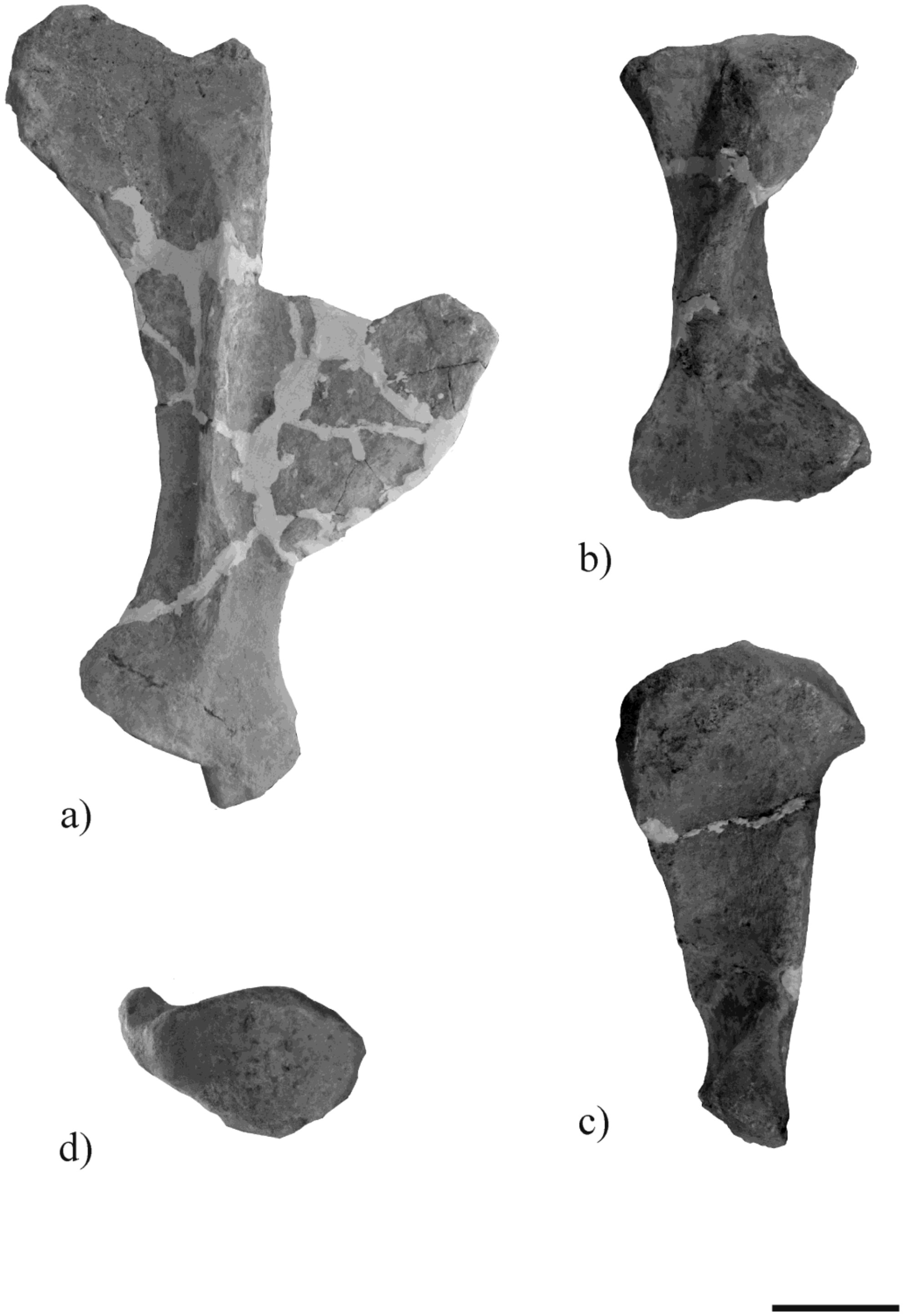
c)



d)

e)

PLATE 6



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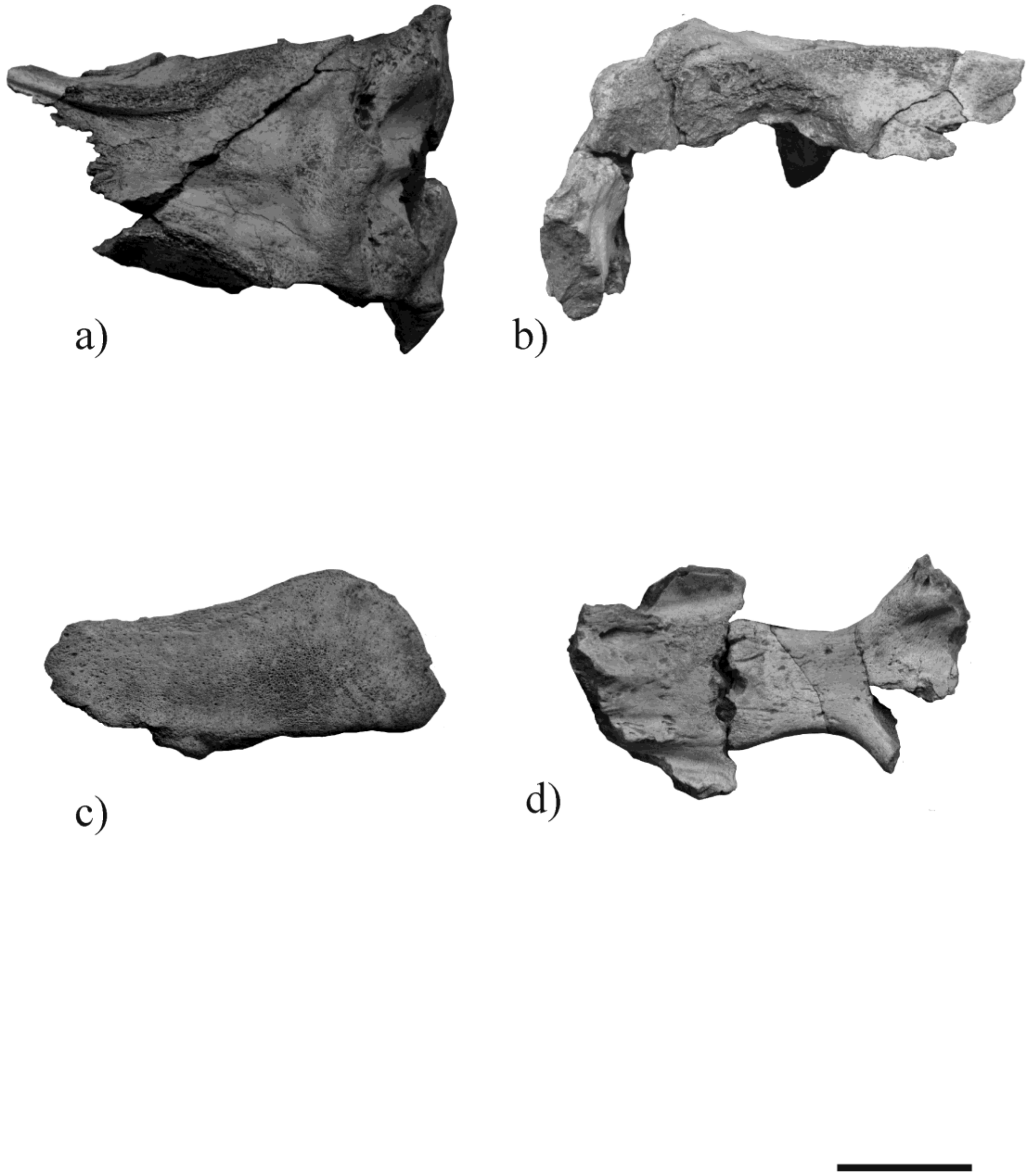

a) b) c) d)

PLATE 8

PLATE 9

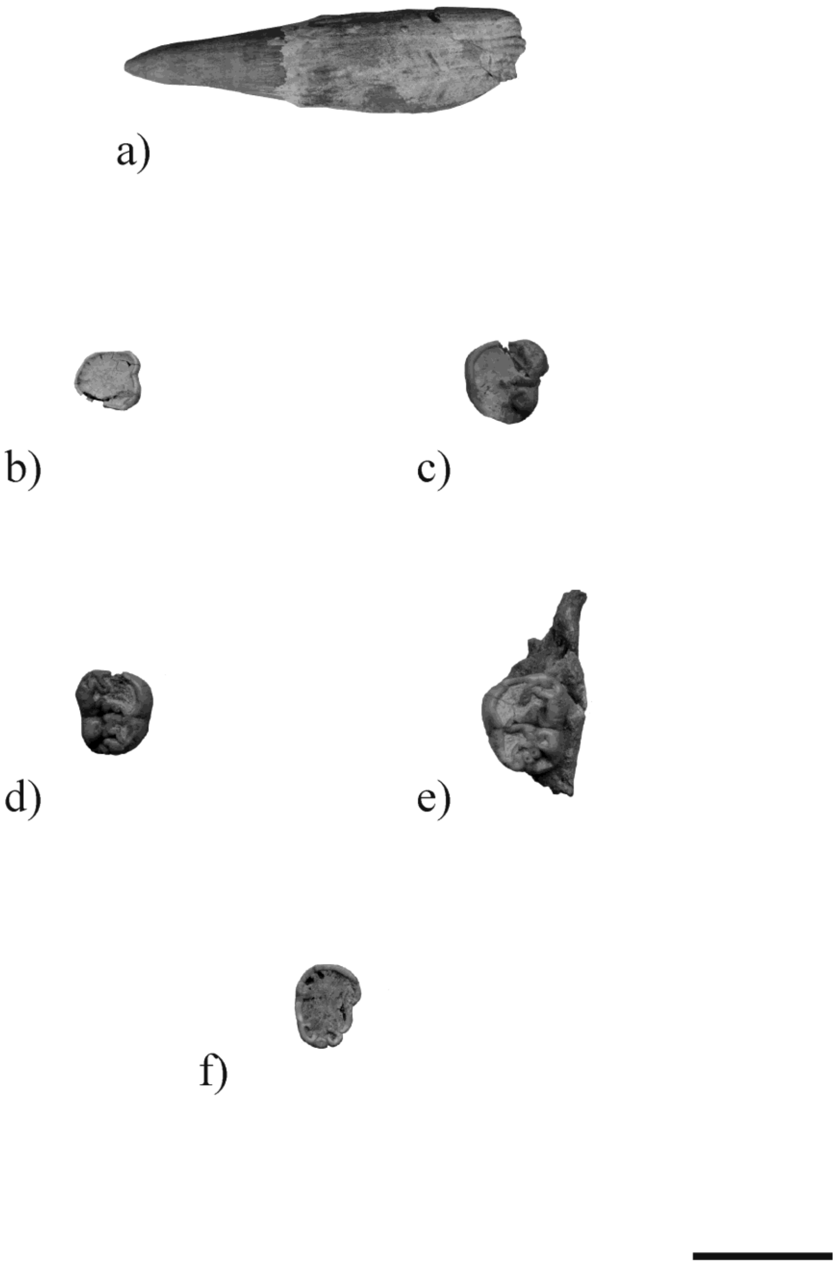

PLATE 10

APPENDICES

APPENDIX 1

1) List of associated fauna in Arcille area.

MOLLUSC FAUNA	
FAMILY	**SPECIES**
BIVALVIA	
Glossidae	*Glossus (Glossus) humanus*
Hiatellidae	*Glycymeris insubrica*
Hiatellidae	*Panopea sp.*
Ostreidae	*Ostrea sp.*
Pectinidae	*Amusium cristatum*
Pectinidae	*Amusium sp.*
Pectinidae	*Cardium hians*
Pectinidae	*Chlamys sp.*
Pectinidae	*Pecten (Pecten) benedictus*
Veneridae	*Dosinia exoleta*
Veneridae	*Dosinia exoleta*
Veneridae	*Dosinia sp.*
Veneridae	*Pelecyora gigas*
Veneridae	*Venus multilamellata*
GASTROPODA	
Bursidae	*Aspa marginata*
Naticidae	*Naticarius sp.*
SCAPHOPODA	
Dentalidae	*Dentalium sexangulum*

OTHER INVERTEBRATE REMAINS
Irregular echinoid spines
Irregular echinoid plates
Regular echinoid spines
Briozoa

OTHER VERTEBRATE REMAINS		
TAXA	**NUMBER OF TEETH FOR EACH SQUARE**	**POSITION OF TEETH IN THE GRID SYSTEM**
FISH TEETH		
Carcharhias taurus	1	g1
Carcharhias taurus	1	k1-k2
Carcharhias taurus	2	c2
Carcharhias taurus	1	d5
Carcharhinus sp.	2	f6
Carcharhinus sp.	1	k1-k2
Carcharhinus sp.	3	d3
Exanchus griseus	1	c5
Galeocerdo cuvieri	1	d6
Isurus hastalis	2	f4
Isurus hastalis	2	e3
Isurus hastalis	1	e4
Sparus sp.	1	j5
Sparus sp.	3	j1
Sparus sp.	1	k1-k2
Sparus sp.	2	c1
Sparus sp.	2	c4
Squatina sp.	2	e3

2) List of associated fauna in Arcille area.

MOLLUSC FAUNA					
POGGIO ALLE MURA		**CAMIGLIANO**		**MONTE ANTICO**	
FAMILY	**SPECIES**	**FAMILY**	**SPECIES**	**FAMILY**	**SPECIES**
BIVALVIA		BIVALVIA		BIVALVIA	
Anomiidae	*Anomia ephippum*	Arcidae	*Anadara* sp.	Arcidae	*Anadara* sp.
Arcidae	*Anadara diluvii*	Cardiidae	*Parvicardium* sp.	Cardiidae	*Parvicardium* sp.
Cardiidae	*Cardium hians*	Carditidae	Glans cf. rudista	Cardiidae	*Acanthocardia echinata*
Cardiidae	*Acanthocardia echinata*	Glycymerididae	*Glycymeris* sp.	Carditidae	Glans cf. rudista
Cardiidae	*Plagiocardium papillosum*	Limopsidae	Limopsis aurita	Glycymerididae	*Glycymeris* sp.
Corbulidae	*Varicorbula gibba*	Lucinidae	*Megaxinus* sp.	Limopsidae	Limopsis aurita
Lucinidae	*Myrtea spinifera*	Veneridae	*Gouldia minima*	Lucinidae	*Megaxinus* sp.
Lucinidae	*Lucinoma boreale*	GASTROPODA		Pectinidae	*Chlamys varia*
Lucinidae	*Lucinella divaricata*	Architectonicidae	*Architectonica* sp.	Pectinidae	*Chlamys multistriata*
Mactridae	*Spisula subtruncata*	Calyptraeidae	*Crepidula* sp.	Pectinidae	*Aequipecten cf. scabrella*
Myidae	*Sphaenia* sp.	Cerithiidae	*Bittium* sp.	Semelidae	*Abra longicallus*
Mytilidae	*Modiolula phaseolina*	Cerithiidae	*Bittium* cf. *lacteum*	Veneridae	*Gouldia minima*
Nuculanidae	*Nucula placentina*	Cerithiidae	*Cerithium vulgatum*	Veneridae	*Timoclea ovata*
Nuculanidae	*Nuculana pella*	Cerithiidae	*Cerithium varicosum*	Veneridae	*Pitar rudis*
Nuculanidae	*Nuculana fragilis*	Columbellidae	*Mitrella scripta*	Veneridae	*Pelecyora brocchi*
Ostreidae	*Ostrea edulis*	Epitoniidae	*Turriscala* sp.	Veneridae	*Dosinia exoleta*
Pectinidae	*Chlamys varia*	Eulimidae	*Melanella* sp.	GASTROPODA	
Pectinidae	*Chlamys multistriata*	Fasciolaridae	*Fasciolaria danconae*	Cerithiidae	*Bittium* sp.
Pectinidae	*Aequipecten cf. scabrella*	Nassaridae	*Nassarius* sp.	Cerithiidae	*Bittium* cf. *lacteum*
Pectinidae	*Amusium cristatum*	Naticidae	*Natica tigrina*	Naticidae	*Natica tigrina*
Pectinidae	*Hyalopecten (Similpecten) similis*	Naticidae	*Neverita josephina*	Naticidae	*Neverita josephina*
Semelidae	*Abra longicallus*	Naticidae	*Lunatia helicina*	Ringiculidae	*Ringicula (Ringiculina) ventricosa*

Semelidae	*Abra* sp.	Pyramellidae	*Turbonilla* sp.	Ringiculidae	*Ringicula* sp.
Tellinidae	*Tellina* sp. 1	Pyramellidae	*Odostomia* sp.	Strombidae	*Strombus coronatus*
Tellinidae	*Tellina* sp. 2	Rissoidae	*Alvania cancellata*	Trochidae	*Jujubinus* sp.
Veneridae	*Venus multilamella*	Strombidae	*Strombus coronatus*	Trochidae	*Calliostoma cf. milionaris*
Veneridae	*Timoclea ovata*	Terebridae	*Strioterebrum reticulare*	Turritellidae	*Archimediella spirata*
Veneridae	*Pitar rudis*	Trochidae	*Solariella* sp.	Turritellidae	*Haustator vermicularis*
Veneridae	*Pelecyora brocchi*	Turritellidae	*Archimediella spirata*	Vermetidae	*Vermetus* sp.
Veneridae	*Dosinia exoleta*	Turritellidae	*Haustator vermicularis*	SCAPHOPOD**A**	
GASTROPODA		Vermetidae	*Vermetus* sp.	Dentaliidae	*Dentalium fossile*
Trochidae	*Jujubinus* sp.	SCAPHOPODA		Dentaliidae	*Dentalium inaequicostatum*
Aporrhaidae	*Aporrhais uttingeriana uttingeriana*	Dentaliidae	*Dentalium fossile*		
Columbellidae	*Columbella sp.*	Dentaliidae	*Dentalium inaequicostatum*		
Muricidae	*Ocinebrina aciculata*				
Nassaridae	*Nassarius semistriatus*				
Naticidae	*Euspira cf. catena*				
Naticidae	*Natica cf. plicatula*				
Pyramidellidae	*Odostomia* sp.				
Pyramidellidae	*Turbonilla cf. lactea*				
Ringiculidae	*Ringicula (Ringiculina) ventricosa*				
Ringiculidae	*Ringicula* sp.				
Rissoidae	*Rissoa* sp.				
Rissoidae	*Alvania cf. discors*				
Trochidae	*Calliostoma cf. milionaris*				
Turritellidae	*Haustator vermicularis*				
Vermetidae	*indet.*				
SCAPHOPODA					
Dentaliidae	*Dentalium fossile*				

Dentaliidae	*Dentalium inaequicostatum*				

OTHER INVERTEBRATE REMAINS
Irregular echinoid spines
Irregular echinoid plates
Regular echinoid spines
Decapod chelae
Balanid plates
Briozoa

OTHER VERTEBRATE REMAINS	
Fish teeth	*Carcharhias taurus*
	Carcharhinus sp.
	Galeocerdo cuvieri
	Isurus hastalis
	Sparus sp.
	Squatina sp.

APPENDIX 2

Measurements of cranial and postcranial bones (in mm) *sensu* Domning (1978; 1988), Bajpai and Domning (1997), and Domning and Pervesler (2001).

Measurements in square brackets were taken from literature and/or illustrations.

Abbreviations: e estimated; L, Length; AW, Anterior Width; PW, Posterior Width;

S, State of teeth and alveoli is also considered, following the table below.

S = State of teeth and alveoli modified from Marsh, 1980					
Tusk on the alveolus		Tusk isolated		Pulp cavity of tusk	
1	unerupted			O	open
2	erupted and unworn	2	unworn	T	tapered at the base
3	erupted and slightly worn	3	slightly worn	C	closed
4	erupted and worn	4	worn		
5	absent, alveolus empty				
Cheek tooth on the alveolus		Cheek tooth isolated		Pulp cavity of cheek tooth	
1	unerupted or partly erupted			O	open
2	erupted and unworn	2	unworn	T	tapered at the base
3	worn just the cusps	3	worn just the cusps	C	closed
4	worn the lophs	4	worn the lophs		
5	worn the entire crown	5	worn the entire crown		
6	broken (stump only in alveolus)				
7	absent, alveolus empty				
8	absent, alveolus partly filled with spongy bone				
9	absent, alveolus not visible				

Measurements of crania of *Metaxytherium subapenninum* (mm)

		MSNTUP I 15892	**GAMPS 62M**	**MC unnum.**	**MGGC 9160**	**IGF 13747**	**DSTG 2523/7**	**NHMB TJ 458**	**PU 13889/1***	**MUSNAF 4960**	**MACPM unnum.**
AB	Condylobasal Lenght			535	525	508				>320	
ab	Height Of Jugal Below Orbit			61	55	54					53
AH	Lenght Of Premaxillary Symphysis	166		229	>210	188					223e
BI	Rear Of Occipital Condyles To Anterior End Of Interfrontal Suture			>218	>245	311					
CC'	Zygomatic Breadth			296	250	275e					255
cc'	Breadth Across Exoccipitals			192	203e	212					
de	Top Of Supraoccipital To Ventral Sides Of Occipital Condyles			185	144e	165					
F	Lenght Of Frontals, Level Of Tips Of Supraorbital Processes To Frontoparietal Suture	162		179	218	200		>128		200e	
LFr	Lenght Of Frontals In Midline	86		>68	130	125	>93e	105	92e	98e	
FF'	Breadth Across Supraorbital Processes			201	170	210		>143			181
ff'	Breadth Across Occipital Condyles			147	120	142					
GG'	Breadth Of Cranium At Frontoparietal Suture	89	60	74	72	70	62e	81	93	70	
gg'	Width Of Foramen Magnum		73	60	68	65	60e				

HI	Lenght Of Mesorostral Fossa	140e		<220	170	163					146e
hi	Height Of Foramen Magnum			52	60e	50					
JJ'	Width Of Mesorostral Fossa	81		73	63	88e					74
KL	Maximum Height Of Rostrum	97		123	145e	130					130
MM'	Posterior Breadth Of Rostral Masticating Surface	85		123	96	98					102e
no	Anteroposterior Lenght Of Zygomatic-Orbital Bridge Of Maxilla		56	69	55	70					53
OP	Lenght Of Zygomatic Process Of Squamosal	136	115	173	165	150e					
OT	Anterior Tip Of Zygomatic Process To Rear Edge Of Squamosal Below Mastoid Foramen			220	210	190e					
P	Lenght Of Parietals, Frontoparietal Suture To Rear Of External Occipital Protuberance			85	75	119	79e	81	93e	91	
Wpmax	Maximum Width Of Parietals Below Level Of Roof	100	94	115	106	102	114e	94	107	96	
pq	Lenght Of Row Of Tooth Alveoli			>74	>95	>70					94
QR	Anteroposterior Lenght Of Root Of Zygomatic Process Of Squamosal	69		69	60	63				58	
rr'	Maximum Width Between Labial			91	87	86					95

	Edges Of Left And Right Alveoli										
ST	Lenght Of Cranial Portion Of Squamosal			126	140e	118					
ss'	Breadth Across Sigmoid Ridges Of Squamosals			261	201	235					
T	Dorsoventral Thickness Of Zygomatic -Orbital Bridge		17	21	17	19					20
tt'	Anterior Breadth Of Rostral Masticating Surface	56		78	70	76					77e
UV	Height Of Posterior Part Of Cranial Portion Of Squamosal			180	161	147			107	150	
WX	Dorsoventral Breadth Of Zygomatic Process		51	77	61	68					
yy'	Maximum Width Between Pterygoid Processes		76	95	65	62e					123e
YZ	Lenght Of Jugal	159		192	182	171					
HSo	Height Of Supraoccipital		64	100	70	67	68e	74	57e		
WSo	Width Of Supraoccipital		100	130	105	95	110e	122		106e	
W/H So	Ratio Of Width To Height Of Supraoocipital		1.5	1.3	1.5	1.4	1.6	1.6			
RD	Deflection Of Masticating Surface Of Rostrum From Occlusal Plane (Degree)	53°		49°	57°	63°					
P/So °	Parietal	110°	120°	95°	127°	97°	124°e	119°	95°	114°	

	Supraoccipital Angle (Degrees)										
TTC	Type Of Temporal Crests	A	A	A	A	A		A	A	A	A

Measurements of mandibles of *Metaxytherium subapenninum (mm)*						
		MSNTUP I15892	**IGPS 213**	**MGGC 9160**	**MUSNAF 4960**	**PU MR-P 172**
AB	Total Lenght	305e	415e	360	320	
AG	Anterior Tip To Front Of Ascending Ramus	240e	250	260	210e	
AP	Anterior Tip To Rear Of Principal Mental Foramen	109e	135	130	110	
AQ	Anterior Tip To Front Of Mandibular Foramen	223e	233	60	177e	
AS	Lenght Of Symphysis	116e	132	150	105e	
BG	Posterior Extremity To Front Of Ascending Ramus	121	165e	155	144	
BQ	Posterior Extremity To Front Of Mandibular Foramen	99	174e	160	162e	
CD	Height At Coronoid Process		270e	>252		
DF	Distance Between Anterior And Posterior Ventral Extremities	182		200	205	135
DK	Height At Mandibular Notch			216e		
DL	Height At Condyle			210		165
EF	Height At Deflection Point Of Horizontal Ramus	132	155	160	62	
EU	Deflection Point To Rear Of Alveolar Row	158e	85	150	110	

GH	Minimum Anteroposterior Breadth Of Ascending Ramus		135	120		105
GP	Front Of Ascending Ramus To Rear Of Principal Mental Foramen	118	138	130	99	
IJ	Maximum Anteroposterio Breadth Of Dorsal Part Of Ascending Ramus		170e	140		
MN	Top Of Ventral Curvature Of Horizontal Ramus To Line Connecting Ventral Extremities	43		50	74	
MO	Minimum Dorsoventral Breadth Of Horizontal Ramus	71e	95	85	86	95
RR^1	Maximum Breadth Of Masticating Surface	35x2	63x2	97	92	
SQ	Rear Of Symphysis To Front Of Mandibular Foramen	150	189e	140	146e	
TU	Lenght Of Alveolar Row	119e	117	>90	>70	93
VV^1	Maximum Width Between Labial Edges Of Left And Right Alveoli			75	92	
WW^1	Minimum Width Between Angles			70	65	
XX^1	Minimum Width Between Condyles			160		
MD	Deflection Of Symphyseal Surface From Occlusal Plane (Degrees)	53°	57°	55°	61°	

Measurements of tusks of *Metaxytherium subapenninum* (mm)

		MSNTUP I15892		**PU 13889/8**	**PU 13889/9**	**from Issel, 1910: 22 (deformed)**		**DSTG 2537**	**MACPM unnum**		**IGPS 218**	**MGGC 9160**	**MC unnum (PU cast)**	**IGF 13747**		**GAMP S 62M**
		left	**right**	**left**	**right**	**left**	**right**		**left**	**right**	**left**	**left**	**right**	**left**	**right**	**right**
Ltot	Total length	>57	>74	> 55	>66	>72e	>72e	>58	>82	>84	>52		200	>70	>70	141
Wclm	Latero-medial width of the crown		22e	22.2	22.0	[22e]	[39e]	24.7	30.0	30.0	28.2	31.3	35.2	24	24	21
Wcap	Antero-posterior width of the crown		26e	23.5	23.1			30.5	38.0	38.0	34.9	42.1	54.8	28	26	26.9
Lpc	Length of protruded crown	20	25e	31	27				28e	28e		20e	65	57	57	67e
Dat	Distance between the anterior tips	52	52						56							
WSlm	Latero-medial diameter of the worn surface										24.1					
WSap	Antero-posterior diameter of the worn surface										33.1		50.0			
S	State of the tusk modified from Marsh, 1980	2 O	2 O	2 O	2 O	2 O	2 O	2 O	2	2	3		4 C	2	2	2 O

Measurements of upper molars of *Metaxytherium subapenninum* (mm)

		IGF 13747		MC unnum		MACPM unnum		IGPS 216	IGPS 217	GAMPS 62M	
		left	**right**	**left**	**right**	**left**	**right**	**left**	**left**	**left**	**right**
DP4	**L**					13e	12e				
	AW					15e	14e				
	PW										
	S					8	8				
DP5	**L**					18.9	19e				
	AW					18.1	18e				
	PW					17.8					
	S					5	6				
M1	**L**			23	28e	20.5	20.3				23
	AW			26	20e	18.7	18.5				24
	PW			24		15.3	15.6				26
	S	9	9	5	7	4	4				5
M2	**L**	27e	26e	28	29	24.8	25.0				
	AW	21e	22	31	32	18.9	18.8			21	
	PW	19e	19e	29	30	17.8	18.0			25	
	S	5	5	5	5	3	3			21	
M3	**L**	32e	31	34	27e	27.8		32	32	28	28
	AW	24e	27	33	23.3	19.8		22	24	24	22,5
	PW	23e	24	31	18.9	16.1		18	23	19	18
	S	5	5	5	5	1		3	3	5	5

Measurements of lower molars of *Metaxytherium subapenninum* (mm)

		MSNTUP I15892		**IGPS 213**	**IGPS 214-215**	**PU MR-P 172**		**PU 13889/5**	**PU 13889/6**	**GAMPS 62 M**
		left	**right**	**left**	**right**	**left**	**right**	**left**	**right**	**left**
pm4	**L**									
	AW									
	PW									
	S									
pm5	**L**		11	19						
	AW		11	15						
	PW		9	15						
	S			5						
m1	**L**	21	20,1	25			23			
	AW	17	17.5	21,2			22			
	PW	15,5	17	20			21			
	S			5			5			
m2	**L**	26,5	28	32	33	31	31			27
	AW	18	19	24	22	25	26			21
	PW	16,5	17,5	25	22e	25.5	26			18
	S			4	4	5	5			
m3	**L**	25e	26e	33		28.7	34	37	36	
	AW	18e	16e	20	17.3	24	27	26.9	27.1	
	PW	20e	14,5e	18	15.8	22.5	26	25.1	25.0	
	S			1	2	5	5	2	2	

Measurements of scapulae of *Metaxytherium subapenninum (mm)*

		MSNTUP I15892	**IGPS 223**	**MGGC 9106**
AB	Maximum lenght , vertebral border to border of glenoid fossa			>380
BI	Mediolateral width of glenoid fossa	54		64
BJ	Lateral border of glenoid fossa to inside of concave distal end of spine	21,2		66
CD	Maximum breadth of blade dorsally			230
EF	Minimun anteroposterior breadth of neck	6,3		56
GH	Maximum anteroposterior breadth of distal end	9		90
KL	Summit of spine to medial side of blade, measured parallel to plane tangent to posterior edges of spine and neck	17,5		42
MN	Anteroposterior length of glenoid fossa	7,05		80
TMO	Length of teres major origin from teres protuberance to posterior corner of blade			105

Measurements of humeri of *Metaxytherium subapenninum (mm)*				
		MSNTUP I15892	**DSTG 2519**	**IGF 8743V**
AB	Maximum length, grater tubercle to distal end	163	197	242
CD	Maximum breadth, greater to lesser tubercle	86	80	108
EF	Maximum breadth, ectepicondyle to entepicondyle	85,5	>45	103
GH	Maximum thickness, posterior side of head to anterior side of greater tubercle	83		
IJ	Maximum thickness, posterior to anterior ends of medial rim of trochlea	25	20	31
KL	Mediolateral breadth of head	55		
MN	Proximodistal breadth of head	53		
OP	Breadth of anterior side of trochlea	66		
QR	Length, saddle between head and grater tubercle to saddle of trochlea	151,5	170	218

APPENDIX 3

Anatomical plates of *Metaxytherium subapenninum* specimens.

Plate 1: Cranium of MSNTUP I15892 in a) right lateral view; b) dorsal view ; c) premaxilla with tusks fixed in their alveoli in dorsal views. Scale bar: 5 cm.

Plate 2: Cranial bones of MSNTUP I15892*:* a) right and left exoccipitals in posterior view; b) left zygomatic process of squamosal in lateral view; c) right zygomatic arch in lateral view. Scale bar: 5 cm.

Plate 3: Mandible of MSNTUP I15892: a) left mandible in lateral view; b) right mandible in lateral view. Scale bar: 5 cm

Plate 4: Molars of MSNTUP I15892: a) left m1 in occlusal view; b) left m2 in occlusal; c) left m2 labial views; d) portion of the right mandible with dp5, m1, m2, m3 in occlusal view. Scale bar: 5 cm

Plate 5: Vertebrae of MSNTUP I15892: a) atlas in anterior view; b) atlas in posterior views; c) odontoid processo f axis in anterior view, d) neural arch of axis in anterior view; e) cervical vertebra in anterior view. Scale bar: 5 cm.

Plate 6: Scapula and humerus of MSNTUP I15892: a) right scapula in lateral view; c) glenoid fossa of right scapula; b) left humerus in anterior view; d) left humerus in lateral view. Scale bar: 5 cm.

Plate 7: Cranium of GAMPS 62M: a) skullcap in dorsal view; b) skullcap in right lateral view; c) left zygomatic process of squamosal in lateral view; d) basioccipital-basisphenoid-presphenoid fragment in dorsal view. Scale bar: 5 cm.

Plate 8: Fragment of the left mandible of GAMP 62M in lateral view. Scale bar: 5 cm.

Plate 9: Upper and lower cheek teeth of GAMP 62M: a) right tusk in lateral view; b) right M1 in occlusal view; b) left M2 in occlusal view; c) right M3 in occlusal view; d) left M3 (with a fragment of maxilla) in occlusal view; e) left m2 in occlusal view. Scale bar: 5 cm.

Plate 10: Sternum of GAMSP 62 M in ventral view. Scale bar: 5 cm.