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RECONSTRUCTING MID-HOLOCENE PALAEOENVIRONMENTAL DYNAMIC IN THE MIDDLE ATLAS (MOROCCO) INFERRED FROM NON-MARINE MOLLUSCS SUCCESSION OF THE AÏT SAÏD OU IDDER TUFF SEQUENCE



Quentin WACKENHEIM ^{1,2}, Nicole LIMONDIN-LOZOUET ¹, Julie DABKOWSKI ¹, Larbi BOUDAD ³ & Jean-François BERGER ⁴

ABSTRACT

The Mediterranean area is particularly sensitive to environmental changes. In Morocco, research undertaken over the past ten years has shown that continental sedimentary archives are useful to document Holocene environmental and climatic variability. However, palaeoenvironmental reconstruction using non-marine molluscs is in an early stage of research. This paper aims to present a new chronostratigraphical and malacological analysis from a Middle-Holocene and Upper Pleistocene tuff sequence in the Middle Atlas (Aït-Saïd-ou-Idder). Results highlight that the lower part of the sequence is dated from the Upper Pleistocene which corresponds to a fluvio-paludal model of deposition. Radiocarbon dates assign the upper part of the sequence to the Middle Holocene. During the Pleistocene phase, the environment is a reed swamp that turns to permanent body water. During the Middle Holocene, three main environmental phases have been identified. Between 6600 and 6100 cal BP, a mesophilic environment is characterised by open and dry areas with some paludal zone. Between 6100 and 5600 cal BP, a durable marshland developed. Between 5600 and 4600 cal BP, the paludal zone tended to disappear while an open and sclerophyllous environment developed. The malacological study provides important elements to the construction of a Holocene malacological framework in Morocco initiated at Blirh (Upper Moulouya). Both records identify a drastic switch to environmental aridification at the end of the Middle Holocene. By recording at the same time local evolution and regional trends and events, Aït Saïd ou Idder results provide material to understand environmental variability in north-eastern Morocco.

Keywords: non-marine molluscs, palaeoenvironment, calcareous tuff, Morocco, Middle Holocene, Upper Pleistocene

RÉSUMÉ

RECONSTITUTION DE LA DYNAMIQUE PALÉOENVIRONNEMENTALE DE L'Holocène MOYEN DANS LE MOYEN ATLAS (MAROC) À PARTIR DE LA SUCCESSION DES MALACOFaUNES CONTINENTALES DU TUF D'AÏT SAÏD OU IDDER.

Les milieux méditerranéens sont des espaces particulièrement sensibles aux changements environnementaux. Au Maroc, les études réalisées ces dix dernières années ont démontré que les archives sédimentaires continentales sont d'excellents enregistrements de la variabilité des environnements holocènes. Cependant, les reconstitutions paléoenvironnementales à partir des assemblages de mollusques continentaux sont encore très peu développées. Ce travail présente une toute nouvelle étude chronostratigraphique et malacologique d'un tuf de l'Holocène moyen et du Pléistocène supérieur dans le Moyen Atlas (Aït Saïd ou Idder). Les résultats démontrent que la séquence datée du Pléistocène supérieur correspond à un tuf de type fluvio-palustre. La partie supérieure est un tuf de versant qui se dépose au cours de la seconde moitié de l'Holocène moyen. La séquence débute au cours du Pléistocène supérieur par une zone marécageuse à roselière à laquelle succède un plan d'eau pérenne dont la végétation avoisinante est plutôt ouverte. Au cours de la seconde moitié de l'Holocène moyen, trois grandes étapes paléoenvironnementales sont identifiées. Entre 6600 et 6100 cal BP, l'environnement mixte est dominé par des zones terrestres assez sèches et ouvertes mais comprend aussi un espace palustre. Puis, entre 6100 et 5600 cal BP une zone marécageuse pérenne se développe. Enfin, entre 5600 et 4600 cal BP l'assèchement et la réduction importante du milieu palustre permet l'augmentation de l'emprise des habitats ouverts et sclérophylles. L'étude malacologique apporte de solides éléments de construction du référentiel malacologique holocène au Maroc initié à Blirh (Haute Moulouya). Les deux séquences enregistrent un changement environnemental caractérisé par une aridification à la fin de l'Holocène moyen. En enregistrant à la fois des évolutions locales mais aussi des dynamiques et événements régionaux, les résultats d'Aït Saïd ou Idder fournissent un support pour comprendre la variabilité des paléoenvironnements du nord-est du Maroc.

Mots-clés : mollusques continentaux, paléoenvironnements, tuf calcaire, Maroc, Holocène moyen, Pléistocène supérieur

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1 - INTRODUCTION

Tufas are freshwater carbonated deposits resulting from calcite precipitation and commonly rich in shells. In palaeoenvironmental studies, such formation presents one of the most reliable sedimentary conditions to achieve palaeoenvironmental analysis (Dabkowski, 2014; Capezzuoli *et al.*, 2014). Land snails occupy a great variety of environments, but each species has a different tolerance determined by temperature, humidity, vegetation and calcium carbonate availability (Puisségur, 1976; Welter-Schultes, 2012). These observations promote continental mollusc assemblages as a reliable bioindicator of past environmental conditions and freshwater tufa as one of the best ecological context for mollusc development and shell preservation. As well as yielding rich assemblages of molluscs, tufa deposits also provide a high resolution palaeoenvironmental signal by the *in situ* preservation of land snail communities over thousands of years (Preece, 1991).

In north-eastern Morocco, research undertaken over the past ten years has shown that continental sedimentary records are important archives of Holocene landscapes and most of the investigations were carried out on paludal and lacustrine deposits in the Middle Atlas (Rhoujjati *et al.*, 2010; Nourelbaït *et al.*, 2014; Cheddadi *et al.*, 2015, 2019; Campbell *et al.*, 2017; Zielhofer *et al.*, 2017) and on fluvial sequence in the Moulouya valley (Zielhofer *et al.*, 2010). Calcareous tufas are common in the Mediterranean basin but, as they are often indurated, their fossil contents have scarcely been studied (Pentecost, 1995; Pedley, 2009). The discovery of a non-indurated formation at Aït Said ou Idder in 2016 was then the opportunity to develop a multi-proxy palaeoenvironmental study on a calcareous tufa in Morocco. Here we present the results of the malacological analysis. Our research was integrated into the program PALEOMEX (INSU-INEE - Work Package 'Transect Maghreb'dir. J.-F. Berger), which discusses environmental and climatic processes and their consequence on Mediterranean societies during the Holocene. This period is characterised by abrupt climatic changes and a strong environmental variability (Alley *et al.*, 1997; Mayewski *et al.*, 2004; Roberts *et al.*, 2011; Fletcher & Zielhofer, 2013; Finné *et al.*, 2019; Roberts *et al.*, 2019) to which Mediterranean landscapes are particularly sensitive (Faust & Zielhofer, 2008; Fletcher & Sanchez-Goñi, 2008; Rohling *et al.*, 2015).

In Morocco, molluscan data have been reported mainly from archaeological contexts (Taylor *et al.*, 2011; Hutterer *et al.*, 2014; Taylor & Bell, 2017) and systematic palaeoenvironmental analysis using malacological assemblages are still in the early stage of research (Limondin-Lozouet *et al.*, 2013). Analyses of fossil molluscan assemblages are based on a palaeoecological approach that involves a broad understanding of modern malacofauna and its habitat. While most of the encountered species are shared with European faunas, identification and ecology of taxa specific to the area are carefully discussed in order to provide accurate palaeoenvironmental information. This paper aims to present the stratigraphy and the malacological

succession of Aït Said ou Idder to discuss the variability of past Holocene landscapes and to complete regional palaeoenvironmental records.

2 - STUDY SITE

2.1 - LOCATION

The 'Aït Said ou Idder' site is located in the north-east of Morocco, 42 km south from the city of Fez (fig. 1A) in the tabular calcareous Middle Atlas (Michard, 1976; Martin, 1981). The deposit is developed on a south-facing slope at 1520 m a.s.l. (fig. 1B). The studied sequence appears nearby P5016 road, 2 km from Dayet Aoua Lake (33°38'49.50"N, 4°59'38.33"W). The exploitation of a former quarry exposed a 45 m-long section of about 3 to 4 m-high where a football field has been established (fig. 1C). At Aït Said ou Idder, tufa deposition is likely to form from calcium-rich water flow from Sidi Mimoun spring 2 km-east from the site. Today, the drainage pattern and the spring are completely canalised for agricultural needs.

2.2 - STRATIGRAPHIC DATA

The 45 m-long tufa locating on a football field and called 'Football section' is divided into three sections: west, central and east (fig. 2). The earliest part of the deposit appears as indurated facies mainly developed in the eastern section of the quarry. Westward, hard levels are less exposed while upper soft deposits thicken. The cumulative stratigraphy of the succession reaches 5 m of thickness and comprises ten consistent lithostratigraphic units (including four grey levels labeled A, B, C and D) detailed below from bottom to top (fig. 2).

- Unit 10: A beige-orange indurated tufa with pluricentimetric oncolithes. This lithostratigraphic unit is visible only in the eastern section and is around 20 cm thick.

- Unit 9: Yellowish indurated layer constituted by encrusted reed reef called 'phytoherm' (Pedley, 1990; fig. 3A) filled by a sandy matrix. This unit represents about 50 to 100 cm.

- Unit 8: Yellowish-orange silty tufa alternating with centimetric rounded oncolithes and laminar layer. The scattered laminar structure is constituted of encrusted chironomid larva burrows (fig. 3B). Oncolithic levels show occasionally a graded bedding. This lithostratigraphic unit varies from 50 cm in the central section to 130 cm in the east section.

- Unit 7: White fine indurated and sometimes powdery tufa including disseminated centimetric oncolithes and laminas in a sandy matrix on its basis. The thickness of this unit is constant in the sequence and reaches 40 cm.

- Unit 6: Silty grey level with phytoclasts (i.e. encrusted plant debris). Grey level D is well developed and corresponds to the entire lithostratigraphic unit 6 (i.e. unit 6 = level D). The lower part of the unit is darker, rich in charcoals and contains decimetric fragments of a white indurated tufa (fig. 3C-D). The grey level is more

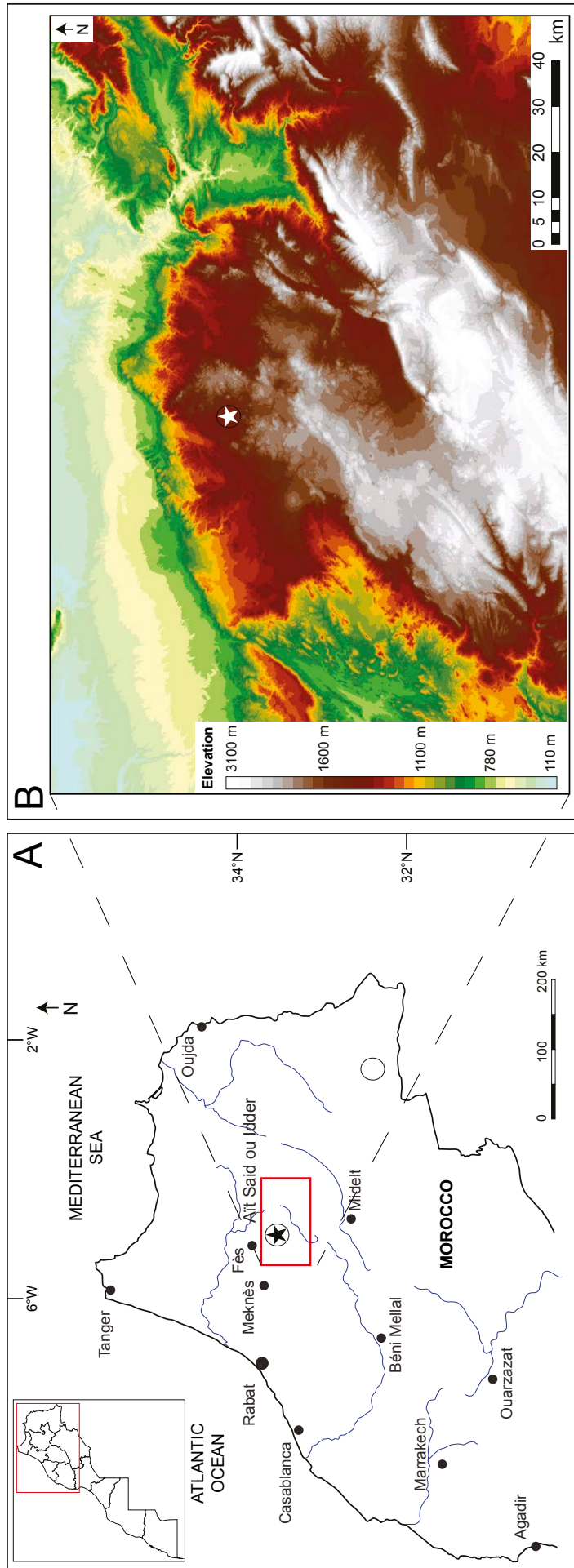
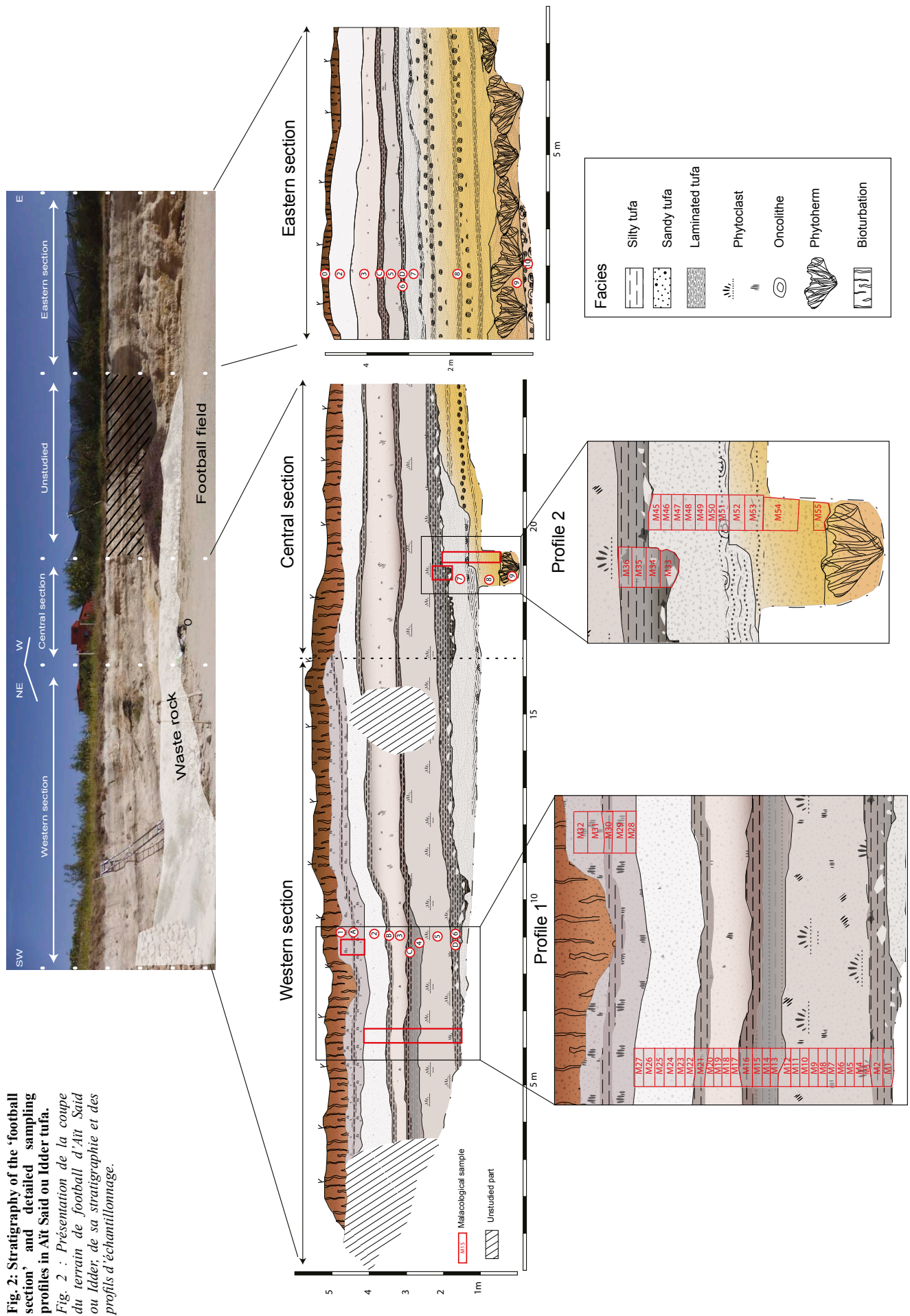


Fig. 1: A Location of Aït Said ou Idder tufa site; B) Digital elevation model of the site surrounding (SRTM 30 m); C) Aït Said ou Idder football section.
Fig. 1 : A Localisation du site; B) Modèle numérique de terrain des environs du site (SRTM 30 m); C) Coupe du terrain de football à Aït Said ou Idder.



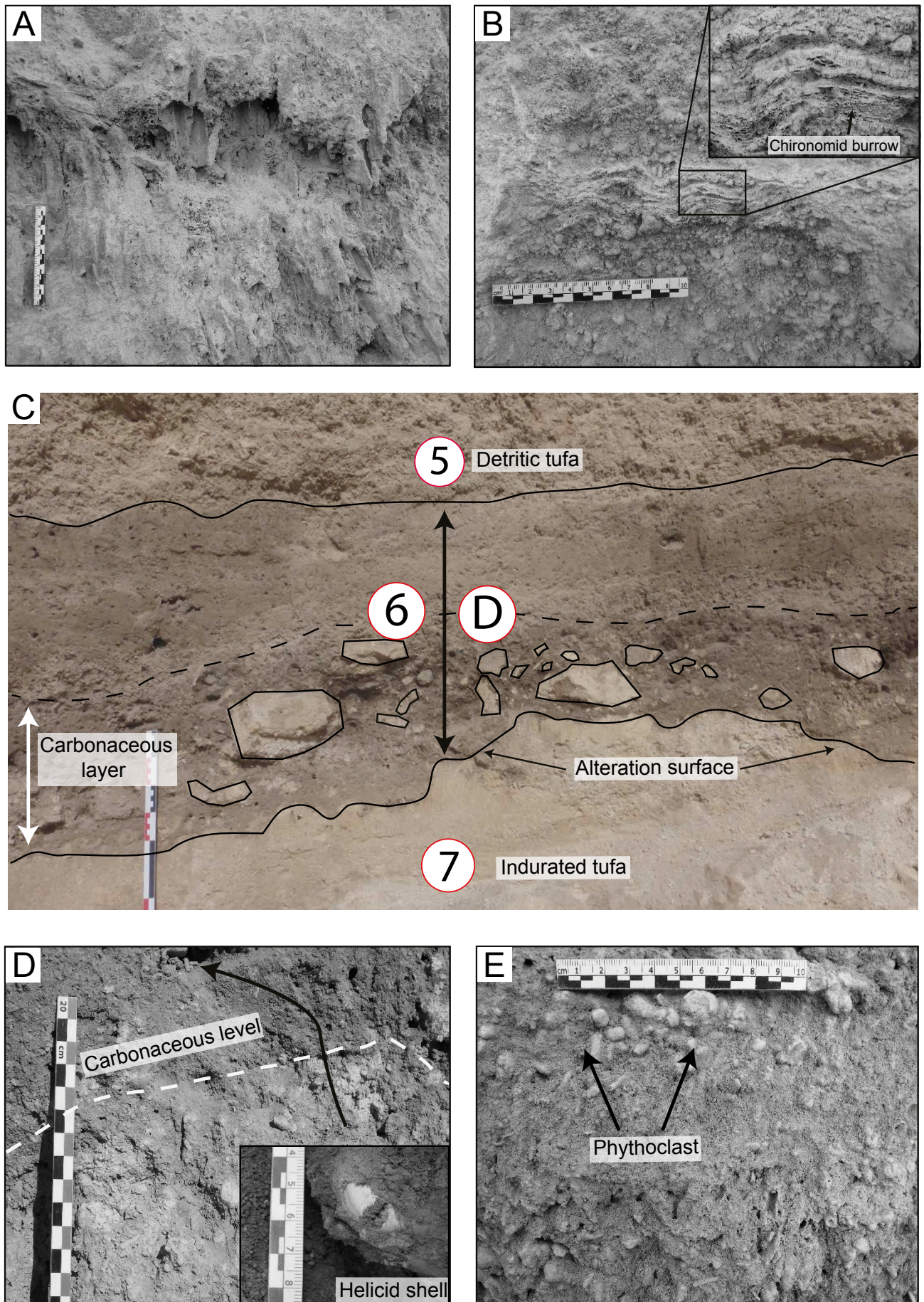


Fig. 3: Plate of the lithofacies observed in Aït Said ou Idder tufa, football section.

A) Phytotherm at the base of the profile (Unit 9); B) Oncolitic levels alternating with encrusted laminae *i.e.* Chironomid burrow; C) Erosional transition between the lower and the upper part of the tufa; D) Zoom of the Unit 6 showing the carbonaceous level; E) Phytoclastic lithofacies of Unit 5.

Fig. 3 : Planche des lithofaciés observés sur la coupe football du tuf d'Aït Said ou Idder A) Phytotherme dans la base de coupe (Unité 9) ; B) Exemple de l'alternance entre des niveaux sableux, à oncolithes et lamines encroutées dans l'unité 8, vue de détail de terrier de chironomid encrouté en coupe ; C) Photo commentée de la zone de transition entre la partie inférieure et supérieure ; D) Vue de détail de l'unité 6 montrant le niveau riche en charbons ; E) Lithofaciés à phytoclastes dans l'unité 5.

expanded in the western and central sections (30 cm) whereas it is only 10 cm thick in the eastern part.

- Unit 5: Loose beige tufa where lenticular silty sands alternating with oncolithic and phytoclastic lithofacies occur. Decimetric to centimetric fragments of encrusted plant reefs are disseminated. The thickness of this level reaches 1 m in the central section and represents only 40 cm in the eastern section.

- Unit 4: Coarser grey tufa with reworked oncolithes and phytoclasts in a silty-sand matrix. Centimetric to decimetric tubular *in situ* encrusted tufa are locally present. The upper part of unit 4 corresponds to the silty grey level C (about 10 cm). In the west section, this unit reaches 30 cm whereas in the rest of the profile it is only represented by the grey level C.

- Unit 3: Coarsely stratified oncolithic and phytoclastic slightly indurated tufa beds alternating with silty levels. The light-grey silty level B (10 cm), only visible on the western and central sections, is present at the top of the unit. This unit is about 50-80 cm in thickness.

- Unit 2: Beige-orange granular tufa with phytoclasts (fig. 3E) in a silty-sand loose matrix. Stratification is diffuse and sometimes lenticular. The thickness of unit 2 is constant along the profile (60-70 cm).

- Unit 1: White-beige homogenous silty tufa containing a centimetric phytoclastic bed, scarce tufa debris and a silty grey level in the middle labelled A (10 cm). This unit is only present in the western section and reaches 40 cm of thickness.

- Unit 0: Modern soil, a silty perturbed level resulting of pedogenesis on the underlying tufa bed.. The thickness of the modern soil is quite constant (20-30 cm) except in the western section where it is reduced due to the erosion.

2.3 - RADIOCARBON DATING

Nine radiocarbon ages were obtained from charcoals and land snail shells (tab. 1). Three were obtained on three different charcoals sampled from the grey layer D. A set of micro charcoals extracted from a sedimentological sample from unit 5 provides one age. Five ages were obtained on samples of mollusc shells picked up from unit 7 (two samples) and from levels A, B and C (one sample each).

Reliable species of land snail have been selected to avoid reservoir effect (i.e. consumption of old carbon by the snails) in the shell (Pigati *et al.*, 2010; Douka, 2017). Raw data are reported as uncalibrated radiocarbon years before 1950 and their equivalent ages expressed in calibrated years before present (BP) using OxCal 4.3 software and IntCal13 calibration curve (Reimer *et al.*, 2013) are given in table 1 and figure 4.

The chronological period covered by the age from unit 5 is large, due to the heterogeneity of the sample (a set of microcharcoals). Considering this uncalibrated age (4730 ± 370 BP), the Holocene chronology seems to show a date inversion, but after calibration the result is consistent with the rest of chronological features (fig. 4). The chronology implied gives confidence on the consistency of the measures obtained from shells.

However, if the ages are regularly distributed along levels A to C, the time interval between levels C and D is much shorter for a similar thickness of deposition. This discrepancy corresponds to the transition from ages obtained on charcoals (level D) to ages obtained on shells (levels C, B, A). However, the rhythmicity of the facies is homogeneous throughout the sequence. Therefore, a possible ageing effect on ages obtained on shells cannot be completely excluded.

2.4 - CHRONOSTRATIGRAPHICAL INTERPRETATION

Field observations allow us to identify two main phases of deposition: the lower and the upper part of the sequence, showing specific sedimentary facies and separated by an erosion surface (fig. 4).

The lower tufa comprises four lithostratigraphic units (10 to 7) which represent up to 3-4 m of the stratigraphy, visible in the eastern section of the profile. Several lateral variations from encrusted reed reef to sandy tufa are particularly noticeable (fig. 2: unit 9). Graded bedding and oncolithe layers imply energetic water flow. Sedimentary features indicate fluvial dynamics alternating spatially and temporally with a swampy environment. Indurated fine tufa, sandy oncolithic bed and phytoherm lithofacies correspond to a fluvio-paludal depositional model (*sensu* Pedley, 1990 & 2009). This lower part is attributed to the Upper Pleistocene as the lithostratigraphic unit 7 and is dated around 40000 a cal BP (tab. 1, fig. 4).

Laboratory code	Sample name	Stratigraphic level	Material	BP	a cal BP (2 σ)	a cal BCE (2 σ)
Poz-83678	Asi16-Ch	Lower part of grey level D	Charcoal	5830 ± 40	6740-6508	4790-4558
Beta-477595	Asi17-Ch3	Lower part of grey level D	Charcoal	5690 ± 30	6553-6405	4604-4456
Beta-477596	Asi17-Ch4	Upper part of grey level D	Charcoal	5470 ± 30	6310-6209	4361-4260
Poz-115941	Asi17-G9	Base of Unit 5	Charcoal	4730 ± 370	6292-4452	4342-2502
SacA-54562	Asi17-M30	Grey level A	<i>Vertigo antvertigo</i>	4375 ± 30	5039-4859	3089-2909
SacA-54563	Asi17-M21	Grey level B	<i>Cochlicella barbara</i>	5085 ± 30	5911-5747	3961-3797
SacA-54564	Asi17-M16	Grey level C	<i>Vertigo antvertigo</i>	5375 ± 30	6280-6019	4330-4096
DeA-17402	I/1889/1	Unit 7	<i>Pupilla muscorum</i>	35920 ± 530	41590-39380	39640-37430
DeA-17403	I/1889/2	Unit 7	<i>Cochlicopa lubrica</i>	36720 ± 570	42170-40150	40220-38200

Tab. 1: Radiocarbon ages obtained from Aït Said ou Idder tufa sequence.

Tab. 1 : Âges radiocarbone obtenus dans le tuf calcaire de Aït Said ou Idder.

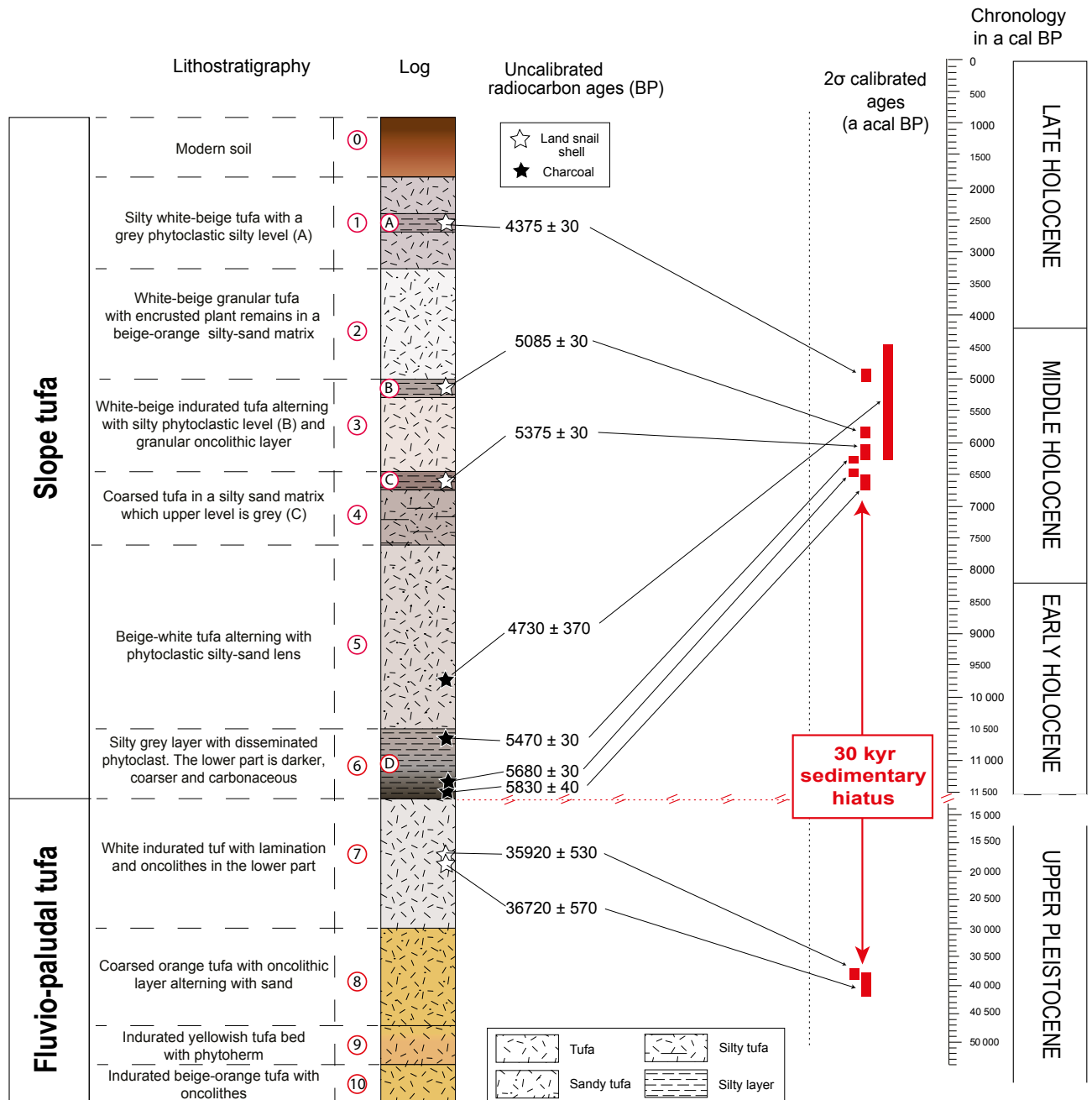


Fig. 4: Lithochronostratigraphical synthesis of the tufa sequence at Aït Said ou Idder.

Fig. 4 : Synthèse lithochronostratigraphique du tuf d'Aït Said ou Idder.

The upper tufa comprises lithostratigraphic units 6 to 1 (including the four grey levels) which represent 2.50 m of the stratigraphy in the west section and around 2 m in the eastern section. All units have a silty matrix light colour from white beige to grey depending on its enrichment in organic matter and in the degree of post-depositional leaching. The encrusted tufa debris are relatively scattered and mainly distributed in level 5. Phytoclast levels correspond to granular levels of detrital tufa (units 1-3). The grey level D, very rich in charcoals and burnt tufa fragments in a very silty matrix, suggests a fire event. Overall, alternation of detrital tufa beds and silty levels is typical of perched spring-line tufa on a slope (Pedley, 2003). These sedimentary facies suggest a mosaic of humid environments on the slope and the development of four periods of relative stabilisation of

the tufa surface. Radiocarbon ages (layers A, B, C and D) indicate that the upper part of the tufa developed between 6800 and 4800 a cal BP (fig. 4). Consequently, the upper tufa episode formed during the second half of the Middle Holocene (fig. 4).

To sum up, the lower part of the sequence is an Upper Pleistocene fluvio-paludal tufa whereas the upper part is a Middle Holocene slope tufa (fig. 4). Unit 6 overlays an eroded surface corresponding to the top of unit 7. Presence of tufa fragments from unit 7 reworked at the base of unit 6 support the interpretation of a strong erosion event between the two phases of tufa accumulation (fig. 3C). This sedimentary hiatus is also identified thanks to radiocarbon ages and corresponds to a time gap of about 30000 years. On Martin (1981) geomorphological map, a "recent" and an "older" tufa are shown; this partition

is likely to correspond to the two phases identified in the football profile.

3 - MALACOLOGICAL SAMPLING AND IDENTIFICATION

Two sampling columns have been made in Aït Said ou Idder tufa to cover the entire sedimentary sequence (fig. 2). A total of 55 malacological samples of a constant volume of 5 litres has been undertaken continuously at 10 cm intervals with local adjustment to stratigraphy (fig. 2). The sediment has been wet sieved on a 500 µm mesh and the residues sorted under a microscope to extract shells. Shells and identifiable fragments have been counted to reach a minimum number of individuals for each sample (Evans, 1972; Limondin-Lozouet, 2002).

In Morocco, modern non-marine molluscs are particularly diversified (Seddon, 1999). Many Holocene taxa are shared with North-West European faunas (Kerney *et al.*, 1999; Limondin-Lozouet *et al.*, 2013) but the taxonomy of some families remains unclear (Rour *et al.*, 2002; Holyoak *et al.*, 2018). Several malacological guides and atlases have been employed to identify the most common land and freshwater molluscs (Van Damme, 1984; Kerney *et al.*, 1999; Gloër, 2002; Welter-Schultes, 2012; Cadeval & Ozozco, 2016). Former Pallary's work (Pallary, 1898; 1899 1900; 1904; 1918; 1919; 1920; 1926; 1928) and recent literature have been consulted to identify specifically Moroccan species (Gittenberger & Ripkens, 1987; Seddon *et al.*, 1994; Seddon & Aparicio, 1998; Van Damme *et al.*, 2010; Holyoak & Holyoak, 2017; Holyoak *et al.*, 2018; Kneubühler *et al.* 2019). Furthermore, modern shells have been collected by handpicking near the site to support the identification and ecological interpretation of fossil material.

4 - MOLLUSCAN ANALYSIS

In total 10169 shells have been extracted from the tufa succession. It comprises 42 taxa, including 26 terrestrial snails (tab. 2).

4.1 - IDENTIFICATION COMMENTS

A big Helicid species was found in six samples of the Holocene tufa (fig. 5: 1-4). These specimens fit with modern shells of *Otala tingitana* (Paladhile, 1875) collected near the site (fig. 5: 4-8) and present all morphological features given in the recent revision of the genus (Holyoak & Holyoak, 2017).

The Geomitridae family is the most problematic to identify because of the high number of species described during the 19th and 20th centuries and the entire lack of systematic revision (Rour *et al.*, 2002). At Aït Said ou Idder, the abundant Geomitridae shells were separated in three morphologically homogeneous groups, respectively referred as Geomitridae sp. 1, Geomitridae sp. 2 and Geomitridae sp. 3. Geomitridae sp. 1 is the most

abundant. It is a 5-6 whorls globular little shell (6-9 mm) with relatively deep sutures (fig. 5: 9-11). The umbilicus is tiny and the mouth rounded with sometimes a slight callus. The shell is white with a brown band, regularly and strongly striated. A modern population showing similar features was found near the site (fig. 5: 12-14). Geomitridae sp. 2 (10 mm) has a bigger umbilicus and a smoother shell (fig. 5: 15-17). It is represented by a unique shell from the Pleistocene part (tab. 2; sample M49). Geomitridae sp. 3 is a little white keeled shell (3-4 mm) with fine irregular striations and a medium umbilicus (fig. 5: 18-20). In the fossil assemblage, this taxon is represented in nine samples and only by juvenile specimens. Geomitridae sp. 3 is morphologically close to an unidentified modern Geomitrid found in Aït Said ou Idder area (fig. 5: 21-26).

A unique specimen named 'Viviparidae' refers to an apex of *Viviparus*-like shell (tab. 2, sample M33). However, the genus was never observed in Africa and no argument supports further identification (Van Damme, 1984; Brown, 1994).

The family range is chosen to name five similar specimens of the same unidentified Hydrobiidae (fig. 5: 27-28). Moroccan Hydrobiids are indeed particularly rich and no extended work on their taxonomy exists (Van Damme *et al.*, 2010).

The generic appellation for *Theodoxus* sp. is adopted for a unique Neritidae operculum.

Although only *Radix labiata* (Rossmässler, 1835) occurs nowadays in Morocco (Van Damme 1984; Taybi *et al.*, 2017), the secure identification of this species requires complete shell specimens or anatomy. *Radix* material from the tufa is always fragmented, consequently, all *Radix*-like shells are called *Radix* sp.

Melanopsis species taxonomy stays unclear because of high intraspecific shell variations (Glaubrecht, 1993; Heller *et al.*, 2005). Specimens from Aït Said ou Idder tufa are designated by *Melanopsis* cf. *praemorsa* (Linnaeus, 1758) because *M. praemorsa* represents actually a complex of species and also the most common species of the genus *Melanopsis* (Van Damme *et al.*, 2010).

4.2 - ECOLOGICAL CLASSIFICATION

Data are presented on distinct ecological and malacological diagrams (Limondin-Lozouet, 2002). The ecological classification in Table 2 is elaborated from Puisségur's groups (1976). Taxa identified without ecological affiliation have been distributed in groups based on knowledge about their habitat and field observations. Geomitridae sp. 1 and sp. 3 are similar to modern Geomitridae observed near the site that occupied exposed herbaceous habitat. Furthermore, most of Geomitridae species in Morocco are considered as xerophilous and were formerly designated by the invalid genus "*Xerophila*". *Cochlicella barbara* and *Rumina decollata* are described as typical species of dry and open habitats (Welter-Schultes, 2012; Cadeval & Ozozco 2016). Moreover in Morocco, *Rumina decollata* is particularly common in open ground places

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Tab. 2: Malacological data classified by ecological groups : xerothermic, open area, mesophilous, paludal, slug, hygrophilous, aquatic.

Tab. 2 : Tableau récapitulatif des données malacologiques ordonnées par groupes écologiques : xérophile, mésophile, limace, hygrophile, aquatique.



Fig. 5: Modern and Holocene molluscs from Aït Said ou Idder and nearby.

1-4: Modern *Otala tingitana* (Paladhile, 1875) from Dayet Aoua; 5-8: *Otala tingitana* (Paladhile, 1875) fossil (unit 6); 9-11: Modern Geomitridae sp., Aït Said ou Idder; 12-14: Geomitridae sp.1 fossil (unit 1); 15-17: Geomitridae sp.2 fossil (unit 7); 18-20: Geomitrida sp.3 fossil (unit 1); 21-23: Juvenile of modern Geomitridae sp., Aït Said ou Idder; 24-26: Adult of modern Geomitridae sp., Aït Said ou Idder; 27-28: SEM view of fossil Hydrobiidae (unit 7). All scale bars = 5 mm except 27-28 scale bar = 0.5 mm & 0.1 mm.

Fig. 5 : Mollusques continentaux actuels et holocènes d'Aït Said ou Idder et des environs. 1-4 : Otala tingitana (Paladhile, 1875) actuel, Dayet Aoua ; 5-8 : Otala tingitana (Paladhile, 1875) fossile (unité 6) ; 9-11 : Geomitridae sp. actuel, Aït Said ou Idder ; 12-14 : Geomitridae sp.1 fossile (unité 1) ; 15-17 : Geomitridae sp.2 fossile (unité 7) ; 18-20 : Geomitrida sp.3 fossile (unité 1) ; 21-23 : Juvenile de Geomitridae sp. actuel, Aït Said ou Idder ; 24-26 : Adulte de Geomitridae sp. actuel, Aït Said ou Idder ; 27-28 : Hydrobiidae fossile (unité 7). Toutes les barres d'échelle font 5 mm en dehors de 27-28 (barre d'échelle = 0.5 mm & 0.1 mm).

such as cultivated areas, grasslands and semi-deserts (Welter-Schultes, 2012). Both species were observed in the surroundings of the Aït Said ou Idder living in xerothermic environments. Consequently, Geomitridae sp. 1, sp. 2, sp. 3, *Cochlicella barbara* and *Rumina decollata* have been assigned to the xerothermic group. The lack of reliable data on *Otala tingitana*'s habitat and its wide range of living environments (Holyoak & Holyoak 2017) support the allocation of this taxon to the mesophilic group.

4.3 - THE MOLLUSCAN SUCCESSION

Malacological data have been plotted as percentages per group in ecological diagrams (fig. 6) and percentages per taxa in frequency histograms (figs. 7 & 8). A threshold of 50 individuals has been used to minimize the risk

of misinterpretation of poorly abundant assemblages. When the total number of individuals in a sample failed to reach 50, results are moderated and represented by hatched areas (fig. 6) or asterisks (figs. 7 & 8). The molluscan succession can be divided into nine biozones based on ecological patterns and on the occurrence and development of taxa. Malacozones 1 and 2 are from the Upper Pleistocene whereas Malacozones 3 to 9 are from the Mid-Holocene tufa.

4.3.1 - The Pleistocene fluvio-paludal tufa

4.3.1.1 - Malacozone 1: M55 to M52 (Unit 8)

This malacozone is composed of an assemblage of mesophilic/open area and paludal/hygrophile/aquatic taxa (fig. 6). *Vallonia pulchella*, *Lauria cylindracea*, *Carychium minimum* and *Melanopsis cf. praemorsa* occur continually in the zone (fig. 7).

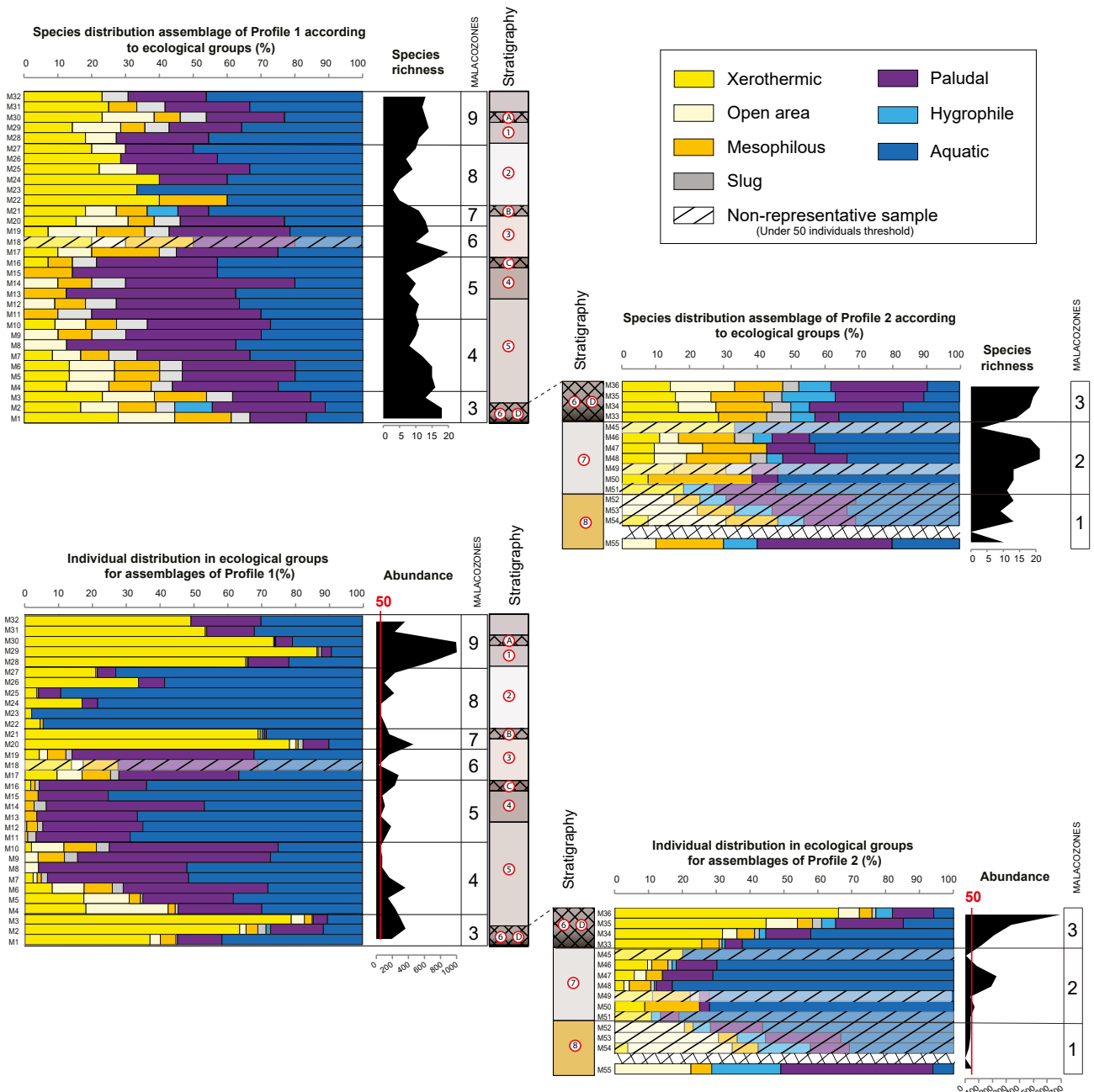


Fig. 6: Malaco-ecological ecological diagrams of the two profiles by species and by individuals.

Curves represents number of species and shell abundance in each sample. Hatched diagrams correspond to non-significant sample where individuals are less than 50.

Fig. 6 : Spectres écologiques des deux profils exprimés par espèces et par individus. La richesse spécifique et l'abondance de chaque échantillon sont représentées par les courbes noires. Les spectres hachurés correspondent aux échantillons non représentatifs dont les effectifs sont inférieurs à 50 individus.

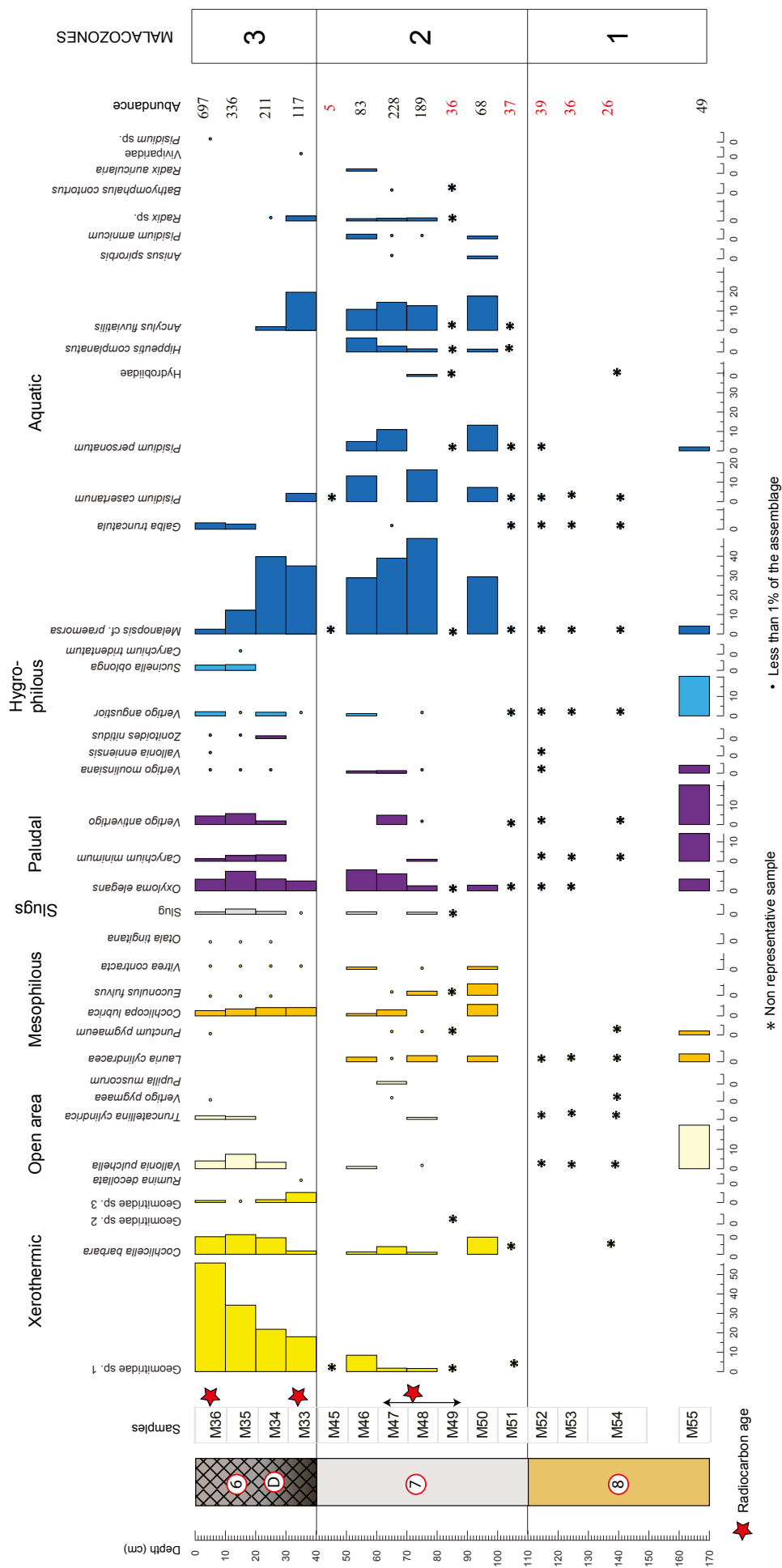


Fig. 7: Percentage frequency histogram of profile 2.

Asterisks represent samples under the threshold of 50 individuals.

Fig. 7 : Diagramme de fréquence spécifique, profil 2. Les astérisques correspondent à des échantillons qui sont en-dessous du seuil de représentativité de 50 individus.

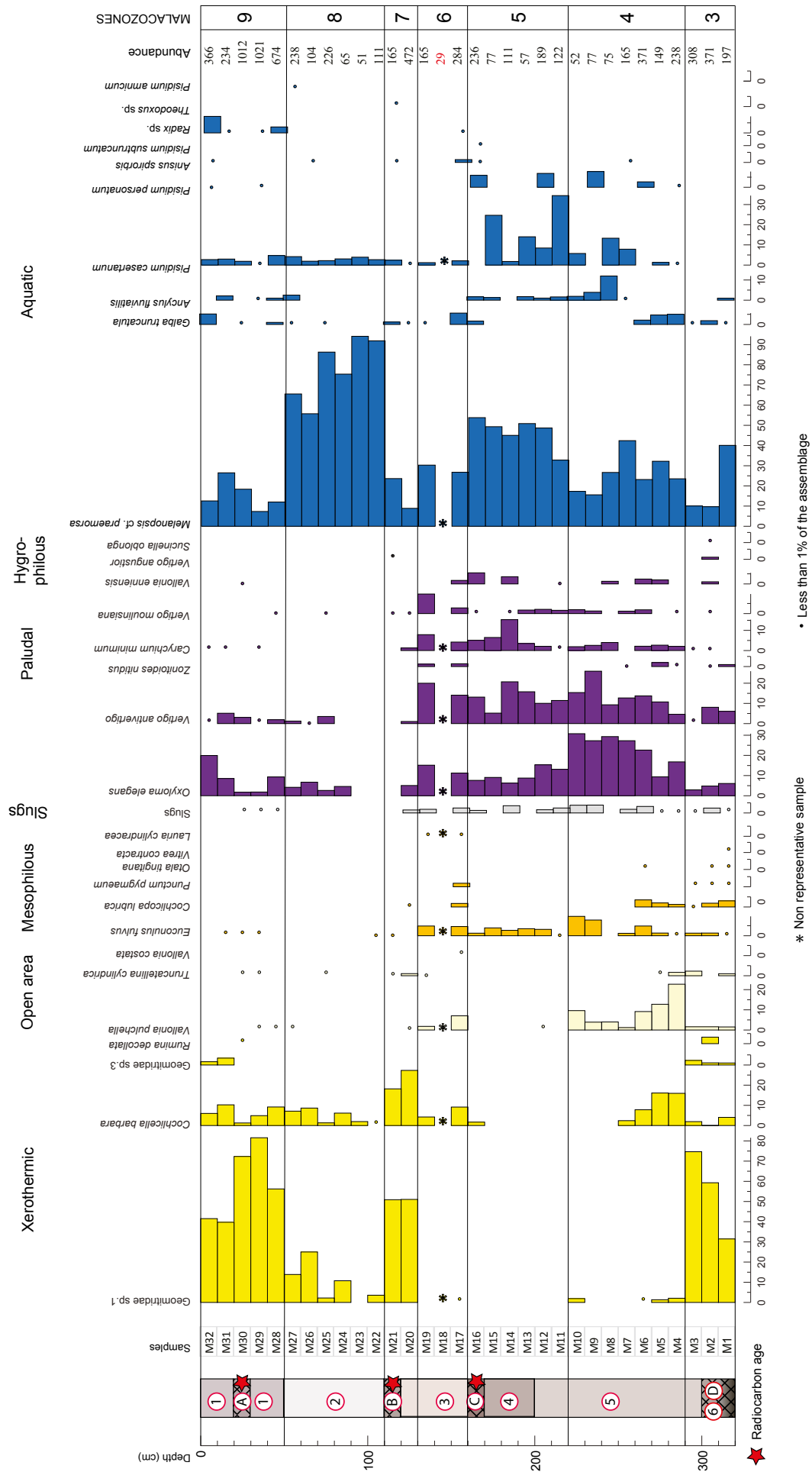


Fig. 8 : Diagramme de fréquence spécifique, profil 1. Les astérisques correspondent à des échantillons qui sont en dessous du seuil de représentativité de 50 individus.

Further investigation will be necessary to draw a precise palaeoecological reconstruction as the threshold of 50 individuals is not reached in any of the sample allocated to MZ 1. Nonetheless, this malacozone suggests a humid environment with patches of open vegetation.

4.3.1.2 - Malacozone 2: M51 to M45 (Unit 7)

The malacozone 2 is characterised by a constant increase in aquatic taxa that represents 40 to 50 % of the assemblage (fig. 6). Malacofaunas show a diversity of 20 freshwater molluscs. Several species arrived such as *Hippeutis complanatus*, *Ancylus fluviatilis*, *Anisus spirorbis*, *Radix* and *Bathyomphalus contortus* (fig. 7). These elements imply the establishment of a durable aquatic habitat. Paludal taxa are mostly represented by *Oxyloma elegans*, a common hygrophilous and marshy Succineidae. The number of xerothermic, mesophilic and open area snails represents 10-15 % of the assemblages. The appearance of *Cochlicopa lubrica*, *Euconulus fulvus* and *Vitrea contracta* indicate an expansion of mesophilic environment. The contribution of xerophilous taxa is minor but Geomitridae sp. 1 and *Cochlicella barbara* slightly increase.

In this part of the succession, some samples show a low number of shells but the whole malacozone presents a reliable data set. Results indicate the development of a durable body of clear water. The adjacent terrestrial open herbaceous environment is quite humid.

4.3.2 - The Mid-Holocene slope tufa

4.3.2.1 - Malacozone 3: M33 to M34 + M1 to M3 (Unit 6 and base of Unit 5)

Malacological assemblages of this third zone particularly contrast with the previous one. They are characterised by the abundance in shells, high diversity and predominance of terrestrial molluscs (tab. 2 and fig. 6). Aquatic species, dominated by the ubiquitous *Melanopsis* cf. *praemorsa*, represent up to 40 % at the base of the zone but quickly decrease to 10-15 % of the assemblage (fig. 6). Xerothermic, open area and mesophilic groups comprise respectively 10 to 15 % of the assemblage diversity. In terms of individuals, xerothermic taxa reach more than 60 % of the assemblage (e.g. sample M36) mainly because of the expansion of Geomitridae sp. 1 (figs. 7 & 8). The occurrence of Geomitridae sp. 3 and *Otala tingitana* is a distinctive feature of the zone indicating the diversification of the xerophilous group. In total, eight species are present within hygrophilous and marshy groups and reach around 40 % of the diversity of the assemblages. Among those, *Vertigo angustior*, *Vertigo moulinsiana* and *Vallonia enniensis* are strong paludal demanding species, which suggest high humidity conditions and a well-developed marshy vegetation (Kerney *et al.*, 1999). Their occurrence thus suggests the development of a small marsh.

Malacofauna is typical of an open and xerophilous vegetation with a permanent humid zone nearby. Following the ratio between aquatic/hygrophile/paludal and xerothermic species on ecological diagrams (fig. 6),

two steps are identifiable in the profile 2 : the first seems to be drier (M33 & M34) while the second records the marsh expansion (M35 & M36).

4.3.2.2 - Malacozone 4: M4 to M10 (Unit 5)

In malacozone 4, the proportion of paludal and aquatic species increases at the expense of xerothermic taxa (fig. 6). Swampy taxa dominate (30 to 50 % of the species diagram). All swampy taxa found at Ait Said ou Idder are registered in this malacozone (fig. 8). Aquatics vary between 20 and 30 % of the species assemblages. The two hygrophiles *Succinella oblonga* and *Vertigo angustior* are absent. The slug occurrence is constant and reflects wet conditions (fig. 8). The xerothermic taxa Geomitridae sp. 1 and *Cochlicella barbara* decline and then disappear whereas aquatic bivalves *Pisidium casertanum* and *Pisidium personatum* appear. The occurrence of *Vallonia pulchella*, an open area taxa which likes humid conditions, is constant in the zone.

The malacological composition of this environmental phase reflects the expansion of a marsh environment with a water supply. In the upper part of the zone, this environment tends to be drained and transformed in a humid grassland.

4.3.2.3 - Malacozone 5: M11 to M16 (Top of Unit 5 + Unit 4)

In Malacozone 5, marsh and aquatic groups remain important, representing about 50 % and 30 % of the specific assemblage (fig. 6). This trend is particularly visible in the diagram of individuals where the sum of aquatic and marshes exceeds 90 % (fig. 6). All xerothermic, mesophilic and open environment taxa disappeared except the mesophilic taxon *Euconulus fulvus*, a tolerant snail that appreciates moist conditions (fig. 8). Despite its preference for wet meadows *Vallonia pulchella* which was well developed in the associations of the previous area (fig. 8), completely disappears. This temporary extinction implies the significant development of a swampy habitat. The slug proportion remains constant in the zone.

The environmental conditions deduced from the malacological assemblages highlight the optimum of a permanent marshy area.

4.3.2.4 - Malacozone 6: M17 to M19 (bottom of Unit 3)

The proportion and diversity of marshy species are very similar to malacozone 5 (figs. 6 & 8). However, in malacozone 6, the decrease in aquatic taxa is balanced by the reappearance and increase of xerothermic, open and mesophilic species (fig. 8): Geomitridae sp. 1, *Cochlicella barbara*, *Vallonia pulchella*, *Truncatellina cylindrica*, *Vallonia costata*, *Punctum pygmaeum* and *Euconulus fulvus*. The sum of xerothermic, open and mesophilic taxa reaches 40 % (fig. 8). The freshwater species are only 20 % of assemblages and are mainly represented by *Melanopsis* cf. *praemorsa* and *Pisidium casertanum*, the occurrence of *Galba truncatula*, *Anisus spirorbis* and *Radix* sp. is occasional (fig. 8).

Zone 6 malacological assemblage indicates the permanence of the marsh and the reappearance of wet grassland habitat on its margins, environmental conditions are similar to the malacozone 4.

4.3.2.5 - Malacozone 7: M20 & M21 (Unit 3)

The Malacozone 7 highlights a dramatic palaeoenvironmental rupture in the succession showing the decrease and disappearance of aquatic and marsh species and the development of xerothermic taxa (fig. 6). This trend is particularly noticeable in the spectra of individuals where xerothermic species represent nearly 70 % of the population (fig. 6). They are mainly represented by Geomitridae sp. 1 and *Cochlicella barbara*, both typical of dry, exposed habitats.

Results from Malacozone 7 illustrate the disappearance of the marsh and the significant development of a drier habitat.

4.3.2.6 - Malacozone 8: M22 to M27 (Unit 2)

Malacozone 8 shows a decrease in species diversity and is mainly composed of aquatic, marshy and xerothermic molluscs. Freshwater taxa represent about 40 to 50 %, swamp molluscs up to 20 % and xerothermic species about 20 to 30 % of the assemblages (fig. 6). Mesophilic and open ground species show few occurrences (fig. 8: *Vallonia pulchella*, *Truncatellina cylindrica* and *Euconulus fulvus*). Slugs disappear during this environmental phase. Marshy taxa are only represented by *Oxyloma elegans*, *Vertigo antivertigo* and a few *Vertigo moulinsiana*. Aquatic species are more diversified but their large individual proportion relies almost exclusively on *Melanopsis* cf. *praemorsa* shells (fig. 8).

Low species diversity and the fact that 80 % of the malacological population is represented by a quasi-mono-specific group of aquatic molluscs suggest a phase of environmental instability that could correspond to a flooding episode.

4.3.2.7 - Malacozone 9: M28 to M32 (Unit 1)

Malacozone 9 is characterised by rich malacological assemblages that show the progression of xerothermic and open area taxa. The sum of xerothermic, open and mesophilic species reaches 30 to 50 % of the assemblages (fig. 6). This malacozone is particularly rich in shells belonging to xerothermic species (i.e. Geomitridae sp. 1) which represent the largest part of the population. The reappearance of Geomitridae sp. 3 and *Rumina decollata* in the top part of the zone is noticeable of drier habitat development. These trends are characteristics of xerophilous vegetation. Swampy taxa are present (*Oxyloma elegans*, *Vertigo antivertigo*, *Carychium minimum*, *Vertigo antivertigo*) but their frequency, although more regular, remains low (fig. 8). Malacozone 9 is also richer in terms of aquatic species (7 taxa) but they comprise a small number of individuals representing about 20 % of the population (fig. 6). Slugs are reappearing with a low frequency.

The malacological succession of zone 9 highlights a much drier terrestrial environment where vegetation is rather open and where sclerophyllous develop at the expense of swampy habitats.

5 - DISCUSSION

5.1 - AÏT SAÏD OU IDDER PALAEOENVIRONMENTAL RECONSTRUCTION

Aït Said ou Idder tufa has been constructed during two main phases. This feature is supported by stratigraphic data, radiocarbon ages and by palaeoenvironmental reconstruction from malacofauna (fig. 9).

According to two radiocarbon ages obtained on shells from the lithostratigraphic unit 7, the first phase (units 10 to 7) is assigned with confidence to the Upper Pleistocene around 40 000 a cal BP (fig. 9). The absence of shells or of other datable material in units 10, 9 and 8 makes it difficult to assess a precise duration and start of this deposition phase. All the units of this phase show coherent lithofacies, rich in oncoliths and phytoherms, indicating a common fluvio-paludal environment. Additionally, no major hiatus is identified within this phase. It may thus correspond to a single stage of deposition. Such a fluvio-paludal model is consistent with the geometry and extent of 'old travertine' mapped by Martin (1981). Mollusc shells are preserved only in the upper part of this phase (fig. 8: Malacozones 1 and 2 in units 8 and 7 respectively) and point to an open environment with a persistent body of water. These data are correlated with the presence of large phytoherm reef and graded bedding in the oncolithic levels (units 8, 9 10). Finally, the Pleistocene record can be divided into two environmental steps: first, a rather dynamic fluvial environment (unit 10), then the development of a swampy reedbed area (units 9-8) which gradually opens up into a permanent body of water where the nearby environment is also open (fig. 8). Malacological and chronological Pleistocene data are not precise enough to allow a reliable comparison with contemporaneous regional records. Consequently, further discussion will focus only on the Holocene data.

During the second main phase of tufa edification, seven radiocarbon ages related to the second half of the Middle Holocene provide a reliable chronological framework for the upper part of the deposit. The erosion surface at the top of unit 7 and fragments of reworked tufa (from unit 7) in the base of unit 6 support an indisputable sedimentary hiatus. Considering the radiocarbon ages, this hiatus between the two phases of tufa deposition lasts ca. 30000 years (fig. 8). The seven rich malacozones defined (MZ 3 to MZ 9) in the Holocene part allow identifying three main palaeoenvironmental steps that are consistent with the different lithostratigraphic units and involved deposition processes (fig. 8).

The first step corresponds to unit 6 malacozone 3 and is characterised by a mosaic landscape composed of marshy and xerophilous open areas. According to radiocarbon

CHRONOSTRATIGRAPHY

MALACOLOGY

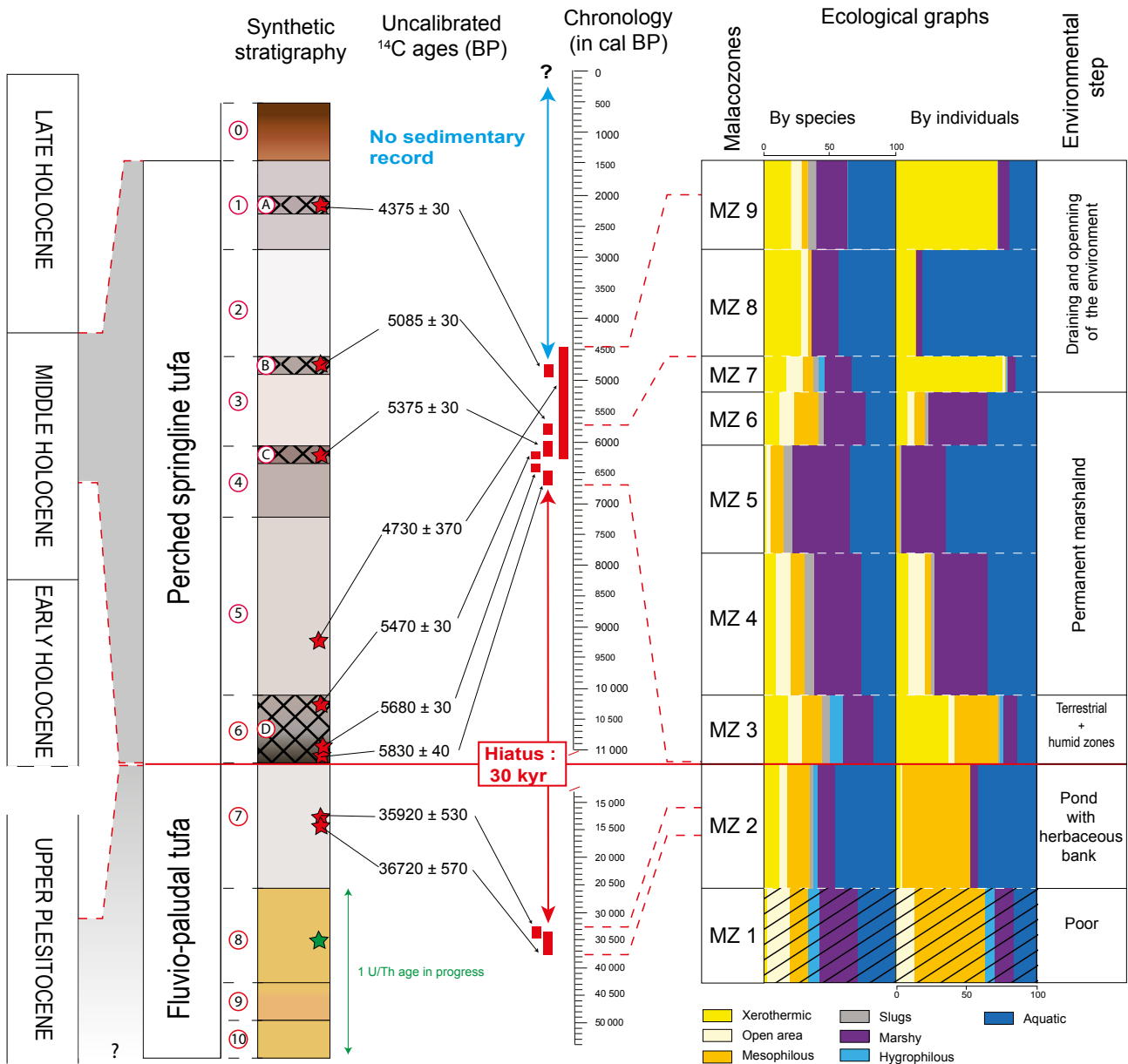


Fig. 9: Synthesis of chronostratigraphical and malacological results.

Fig. 9 : Synthèse des résultats malacologiques, stratigraphiques et de la chronologie.

dating, at the beginning and at the end of the level, this phase lasted about 500 years and corresponds to a period between 6209 cal BP and 6740 a cal BP. representing around 30 cm of thickness. This carbonaceous silty level (unit 6) is particularly rich in shells and shows a good species diversity. The xerophilous environment deduced from this step is consistent with the occurrence of a possible fire event recorded at the base of unit 6. Lithological observation and environmental reconstruction deduced from molluscs indicate a phase of stabilisation characterised by the development of terrestrial habitat. More arid climatic conditions could have stimulated the occurrence of fires which may have contributed to opening up the vegetation.

During the next two environmental steps, lithological

succession shows an alternation between detrital tufa layers and grey levels.

The second environmental step concerns the development of a permanent wetland area (units 5 to 3) between at least 6100 and 5600 a cal BP. (MZ4 to MZ6, lasting about 600 years) according to radiocarbon ages from level B (fig. 8). The sediment thickness between level D and B represents 1.65 m. While the stratigraphy comprises a well-identified grey level (C) interstratified between two silty detrital tufa beds, the swampy environment recorded in the malacological succession is constant. Local variations on the extension of marshy habitats exist but the optimum of the swampy area is reached during the malacozone 5 which indicates particularly humid environmental conditions.

The last environmental step (units 2 & 1; MZ7 to MZ9) corresponds to the end of the Middle Holocene and records at least 1000 years of environmental history (5600-4600 a cal BP) according to ages from levels B and A for a thickness of 1 m (fig. 8). This period is characterised by a significant reduction of the marsh, which is replaced by open and sclerophyllous habitats. A record of a flooding event in the beginning of the period is correlated with the silty-sand unit 2 where the mollusc diversity is poor (fig. 6) and mostly represented by the tolerant taxa *Melanopsis* cf. *praemorsa* (fig. 8). The development of xerophilous snail populations, an indicator of dry habitats, is linked to grey levels B and A.

5.2 - AÏT SAÏD OU IDDER HOLOCENE RECORD IN THE REGIONAL CONTEXT

In North Morocco, the Blirh succession in Moulouya fluvial sediments provides a detailed malacological succession for almost all the Holocene except the first part of the Middle Holocene (Limondin-Lozouet *et al.*, 2013). Aït Said ou Idder sequence thus partly fills the time hiatus of Blirh and overlaps the record of the second half of the Middle Holocene. At Blirh, the malacofauna assemblages show a drastic environmental rupture around 5100 a cal BP from aquatic and swampy environments to open and dry landscapes (Limondin-Lozouet *et al.*, 2013). A similar environmental pattern is observed at Aït Said ou Idder around 5600 a cal BP when the permanent marshland is replaced by well-drained and open habitats (fig. 9). The 500-year difference could be explained by the radiocarbon dating based on shells at Aït Said ou Idder while on charcoals at Blirh: Aït Said ou Idder dating on shells may give ages older than the real one for this phase of deposition. Further analyses and accurate dating are needed to improve the comparison between these malacological records but both sites provide consistent reconstructions of major environmental events at a regional scale. The environmental rupture recorded by both malacological successions is likely to be contemporaneous with a global climatic change at the end of the Middle Holocene which corresponds to a switch to dry conditions in the Mediterranean region (Roberts *et al.*, 2011; Bini *et al.*, 2019). This environmental shift appears during an interval of forest decline (Fletcher *et al.*, 2013) and corresponds to the end of the African Humid Period (deMenocal *et al.*, 2000) and to a period of Rapid Climate Change (Mayewski *et al.*, 2004; Fletcher & Zielhofer, 2013).

Additionally, in North-East Morocco, considering the set of available ages, Middle Atlas lakes and peat sequence provide consistent Holocene records to be compared with the Aït Said ou Idder results (Lamb & Kaars, 1995; Cheddadi *et al.*, 1998; Rhoujjati *et al.*, 2012; Nourelbaït *et al.*, 2014; Nourelbaït *et al.*, 2016; Campbell *et al.*, 2017; Zielhofer *et al.*, 2017).

The bottom of Iffer, a part of Tiguelmamine and Sidi Ali sequences are also contemporaneous to the first

environmental Aït Said ou Idder phase (6700-6200 cal BP). During this period of the Middle Holocene, at Iffer and Sidi Ali, sedimentary data show a low level of the lakes explained by a low water input (Rhoujjati *et al.*, 2012; Zielhofer *et al.*, 2017). Furthermore, these elements are corroborated both by peaks of Poaceae pollen at Sidi Ali and Tiguelmamine, that imply an episode of rapid environmental opening (Lamb & Kaars, 1995; Campbell *et al.*, 2017; Zielhofer *et al.*, 2017) and by an increase of temperatures modeled from Tiguelmamine pollen data (Cheddadi *et al.*, 1998). The sum of these different regional records supports a period of aridity around 6500-6400 a cal BP which is also identified by an increase of semi-arid taxa in the pollen diagram of the Alboran Sea marine core (Fletcher & Sanchez-Goni, 2008). Aït Said ou Idder fire event which may have contributed to opening up the vegetation as recorded by the mollusc succession, can be explained by regional arid climatic conditions.

During the Aït Said ou Idder phase of marshy expansion (6100-5600 a cal BP), more humid climatic conditions based on variations in oxygen isotopes of ostracod shells and high level of the lake are indicated at Sidi Ali (Zielhofer *et al.*, 2017) as well as cooler temperatures from modelisation at Tiguelmamine (Cheddadi *et al.*, 1998). This period is also well recorded in the Ras el Ma peat sequence (Nourelbaït *et al.*, 2014). In terms of pollen records at Ras el Ma, Tiguelmamine and Sidi Ali, this period is marked by a slight reduction of tree and shrubs taxa that imply an opening of the landscape (Lamb & Kaars, 1995; Nourelbaït *et al.*, 2014; Campbell *et al.*, 2017). Thus regional environmental conditions related to different records appear consistent with malacological results.

Between 5600 and 4600 a cal BP, when drier conditions are emphasized by the mollusc succession at Aït Said ou Idder, in Tiguelmamine and Sidi Ali sequences, pollen indicate variations in the vegetation composition: some aridification evidence are identified but forest and shrub taxa persist (Lamb & Kaars, 1995; Campbell *et al.*, 2017). Geochemical results on ostracod shells show a quite drier climate without demonstrating an evident pattern of aridification (Zielhofer *et al.*, 2017). During this period a strong climatic and environmental variability is noticeable, for instance, a cold event recorded between 5000 and 5500 a cal BP in Dayet Hachlaff sequence (Nourelbaït *et al.*, 2016). From 5000 a cal BP, evidence of landscape aridification is identified in Dayet Hachlaff's pollen sequence ten kilometers south of the site by a slight reduction of arboreal vegetation (Nourelbaït *et al.*, 2016). During this period, palaeoenvironmental records differ locally and identifying regional trends remains difficult.

6 - CONCLUSIONS

The chronostratigraphic study of the tufa sequence identified two main deposition phases corresponding to a basal fluvio-paludal tufa allocated

to the Upper Pleistocene and a tufa slope dated from the Middle Holocene. This study leads to the following conclusions:

- the Upper Pleistocene fluvio-paludal phase dated around 40000 a cal BP records three main environmental stages: first, an aquatic environment, then a swampy area with reed beds, finally followed by a permanent body of water whose neighbouring vegetation is rather open;

- three major phases of environmental history have been identified from the Holocene slope tufa malacological succession. The first step corresponds to a mixed environment comprising a marsh and a better-drained grassland area. The second step indicates a durable marshy area. The last step presents the drying out and a significant reduction of the swampy environment, which is being replaced by open and sclerophyllous habitats;

- the malacological study provides important elements to the construction of a Holocene malacological referential in Morocco initiated by the malacological succession of Blirh. Both records identify a drastic switch to environmental aridification at the end of the Middle Holocene. Mollusc successions provide a reliable reconstruction of local environmental evolution and also allow identifying regional and supra-regional environmental trends and events;

- the succession of Aït Said or Idder completes other regional paleoenvironmental data, particularly during the Middle Holocene, and provides material to understand landscape variability in northeastern Morocco. The first phase of mosaic of environment and fire events is consistent with the aridification of climatic conditions recorded in the area (low lake level and pollen reconstruction). More humid climatic conditions registered by oxygen isotopes from ostracod shells at Sidi Ali are contemporaneous with the Aït Said ou Idder marshy expansion. The final switch to drier environments is not evidenced by other regional biological proxy studies because of a climatic and environmental variability but is echoed in Dayet Hachlaff sequence.

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REFERENCES

- ALLEY R.B., MAYEWSKI P., SOWERS T., STUIVER M., TAYLOR K.C. & CLARK P.U., 1997 - Holocene climatic instability: a prominent widespread event 8200 yr ago. *Geology*, **25**, 483-486.
- BINI M., ZANCHETTA G., PERȘOIU A., CARTIER R., CATALÀ A., CACHO I., DEAN J.R., DI RITA F., DRYSDALE R.N., FINNÉ M., ISOLA I., JALALI B., LIRER F., MAGRI D., MASI A., MARKS L., MERCURI A.M., PEYRON O., SADORI L., SICRE M.-A., WELC F., ZIELHOFFER C. & BRISSET E., 2019 - The 4.2 ka B.P. Event in the Mediterranean region: an overview. *Climate of the Past*, **15**, 555-577.
- BROWN D.S., 1994 - *Freshwater snails of Africa and their medical importance*. Taylor & Francis, 2d edition, Londres, 673 p.
- CADEVAL J. & OZOZCO A., 2016 - *Caracoles y Babosas de la Peninsula Iberica y Baleares*. Omega, Barcelona, 817 p.
- CAMPBELL J.F.E., FLETCHER W.J., JOANNINS., HUGHES P.D., RHANEM M. & ZIELHOFFER C., 2017 - Environmental Drivers of Holocene Forest Development in the Middle Atlas, Morocco. *Frontiers in Ecology and Evolution*, **5**, 1-22.
- CAPEZZUOLI E., GANDIN A. & PEDLEY M., 2014 - Decoding tufa and travertine (fresh water carbonates) in the sedimentary record: The state of the art. *Sedimentology*, **61** (1), 1-21.
- CHEDDADI R., LAMB H.F., GUIOT J. & VAN DER KAARS S., 1998 - Holocene climatic change in Morocco: a quantitative reconstruction from pollen data. *Climate dynamics*, **14** (12), 883-890.
- CHEDDADI R., NOURELBAIT M., BOUAÏSSA O., TABEL J., RHOJJATI A., LÓPEZ-SÁEZ J.A., ALBA-SÁNCHEZ F., KHATER C., BALLOUCHE A., DEZILEAU L. & LAMB H., 2015 - A History of Human Impact on Moroccan Mountain Landscapes. *African Archaeological Review*, **32**, 233-248.
- CHEDDADI R., PALMISANO A., LÓPEZ-SÁEZ J.A., NOURELBAIT M., ZIELHOFFER C., TABEL J., RHOJJATI A., KHATER C., WOODBRIDGE J., LUCARINI G., BROODBANK C., FLETCHER W.J. & ROBERTS C.N., 2019 - Human demography changes in Morocco and environmental imprint during the Holocene. *The Holocene*, **29** (5), 816-829.
- DABKOWSKI J., 2014 - High potential of calcareous tufas for integrative multidisciplinary studies and prospects for archaeology in Europe. *Journal of Archaeological Science*, **52**, 72-83.
- DEMENOCAL P., ORTIZ J., GUILDERTSON T., ADKINS J., SARNSTEIN M., BAKER L. & YARUSINSKY M., 2000 - Abrupt onset and termination of the African Humid period: rapid climate responses to gradual insolation forcing. *Quaternary Science Review*, **19**, 347-361.
- DOUKA K., 2017 - Radiocarbon dating of marine and terrestrial shells. In M.J., Allen (ed.), *Molluscs in Archaeology. Methods, approaches and applications*. Oxbow Books, Oxford, 381-399.
- EVANS J.G., 1972 - *Land snails in Archaeology. With special reference to the British Isles*. Seminar Press, London, 426 p.
- FAUST D. & ZIELHOFFER C., 2008 - The last 15 ka of environmental change in Mediterranean regions interpreting different archives. *Quaternary International*, **181**, 1-3.
- FINNÉ M., WOODBRIDGE J., LABUHN I. & ROBERTS N.C., 2019 - Holocene hydro-climatic variability in the Mediterranean: A synthetic multi-proxy reconstruction. *The Holocene*, **29** (5), 847-863.
- FLETCHER W.J. & SANCHEZ-GOÑI M.F., 2008 - Orbital and sub-orbital-scale climate impacts on vegetation of the western Mediterranean basin over the last 48,000 yr. *Quaternary Research*, **70** (3), 451-464.
- FLETCHER W.J., DEBRET M. & SANCHEZ-GOÑI M.F., 2013 - Mid-Holocene emergence of a low-frequency millennial oscillation in western Mediterranean climate: Implications for past dynamics of the North Atlantic atmospheric westerlies. *The Holocene*, **23** (2), 153-166.
- FLETCHER W.J. & ZIELHOFFER C., 2013 - Fragility of Western Mediterranean landscapes during Holocene rapid climate changes. *Catena*, **103**, 16-29.
- GITTENBERGER E. & RIPKEN T.E.J., 1987 - The genus *Theba* (Mollusca: Gastropoda: Helicidae): Systematics and distribution. *Zoologische Verhandlungen*, **241**, 1-62.
- GLAUBRECHT M., 1993 - Mapping the diversity: Geographical distribution of the freshwater snail Melanopsis (Gastropoda: ? Cerithioidea: Melanopsidae) with focus on its systematics in the Mediterranean basin. *Mitteilungen aus dem Hamburgischen Zoologischen Museum und Institut*, **90**, 41-97.
- GLÖER P., 2002 - *Die Süßwassergastropoden Nord- und Mitteleuropas. Bestimmungsschlüssel, Lebensweise, Verbreitung. Die Tierwelt Deutschlands*. ConchBooks, Hackenheim, 327 p.

- HELLER J., MORDAN P., BEN-AMI F. & SIVAN N., 2005 - Conchometrics, systematics and distribution of Melanopsis (Mollusca: Gastropoda) in the Levant. *Zoological Journal of the Linnean Society*, **144** (2), 229-260.
- HOLYOAK D.T. & HOLYOAK G.A., 2017 - A Revision of the land-snail genera *Otala* and *Eobania* in Morocco and Algeria. *Journal of Conchology*, **42** (6), 419-490.
- HOLYOAK D.T., HOLYOAK G.A., CHUECA L.J. & GOMEZ MOLINER B.J., 2018 - Evolution and taxonomy of the populations of *Eremina* (Gastropoda, Pulmonata, Helicidae) in Morocco. *Journal of Conchology*, **43**, 17-57.
- HUTTERER R., LINSTÄDTER J., EIWANGER J. & MIKDAD A., 2014 - Human manipulation of terrestrial gastropods in Neolithic culture groups of NE Morocco. *Quaternary International*, **320**, 83-91.
- KERNEY M.P., CAMERON R.A.D. & BERTRANDA., 1999 - *Guide des escargots et limaces d'Europe*. Delachaux et Nieslé, Paris, 370 p.
- KNEUBÜHLER J., HUTTERER R., PFARRER B. & NEUBERT E., 2019 - Anatomical and phylogenetic investigation of the genera *Alabastrina* Kobelt, 1904, *Siretia* Pallary, 1926, and *Otala* Schumacher, 1817 (Stylommatophora, Helicidae). *ZooKeys*, **843**, 1-37.
- LAMB H.F. & VAN DER KAARS S., 1995 - Vegetational response to Holocene climatic change: pollen and palaeolimnological data from the Middle Atlas, Morocco. *The Holocene*, **5**, 400-408.
- LIMONDIN-LOZOUET N., 2002 - Les mollusques continentaux. In J.-C. Miskovsky (ed.), *Géologie de la Préhistoire*, GEOPRE, Perpignan, 773-784.
- LIMONDIN-LOZOUET N., HADDOUMI H., LEFEVRE D., GHAMIZI M., AOURAGHE H. & SALEL T., 2013 - Holocene molluscan succession from NE Morocco: Palaeoenvironmental reconstruction and biogeographical implications. *Quaternary International*, **302**, 61-76.
- MARTIN J., 1981 - *Le Moyen Atlas Central : étude géomorphologique*. Notes et Mémoires du Service géologique du Maroc, **258**, 445 p.
- MAYEWSKI P.A., ROHLING E.E., STAGER J.C., KARLEN W., MAASCH K.A., MEEKER L.D., MEYERSON E.A., GASSE F., VAN KREVELD S., HOLMGREN K., LEE-THORP J., ROSQVIST G., RACK F., STAUBWASSER M. & SCHNEIDER R.R., STEIG E.J., 2004 - Holocene climate variability. *Quaternary Research*, **62**, 243-255.
- MICHARD A. 1976 - *Eléments de géologie marocaine*. Notes et Mémoires du service géologique du Maroc, **252**, 408 p.
- NOURELBAÏT M., RHOJJATI A., EYNAUD F., BENKADDOUR A., DEZILEAU L., WAINER K., GOSLAR T., KHATER J., TABEL J. & CHEDDADI R., 2014 - An 18 000 year pollen and sedimentary record from the cedar forests of the Middle Atlas, Morocco. *Journal of Quaternary Science*, **29** (5), 423-432.
- NOURELBAÏT M., RHOJJATI A., BENKADDOUR A., CARRÉ M., EYNAUD F., MARTINEZ P. & CHEDDADI R., 2016 - Climate change and ecosystems dynamics over the last 6000 years in the Middle Atlas, Morocco. *Climate of the Past*, **12**, 1029-1042.
- PALLARY P., 1898 - Première contribution à l'étude de la faune malacologique du Nord-Ouest de l'Afrique. *Comptes rendu de l'Association française pour l'Avancé des Sciences*, **27** (2), 556-563.
- PALLARY P., 1899 - Deuxième contribution à l'étude de la faune malacologique du Nord-Ouest de l'Afrique. Supplément à 'La faune malacologique du Maroc' d'A. Morelet. *Journal de Conchyliologie*, **46** (2), 49-170.
- PALLARY P., 1900 - Troisième contribution à l'étude de la faune malacologique du Nord-Ouest de l'Afrique. *Comptes rendus de l'Association française pour l'avancement des sciences*, (2), 731-735.
- PALLARY P., 1904 - Quatrième contribution à l'étude de la faune malacologique du Nord-Ouest de l'Afrique. Deuxième supplément à la 'Faune malacologique du Maroc' d'A. Morelet. *Journal de Conchyliologie*, **52** (1), 5-58.
- PALLARY P., 1918 - Diagnoses d'une cinquantaine de mollusques terrestres nouveaux du Nord de l'Afrique. *Bulletin de la Société d'histoire naturelle de l'Afrique du nord*, **9** (7), 137-152.
- PALLARY P., 1919 - Hélicidées nouvelles du Maroc. 2^e Partie. *Journal de Conchyliologie*, **64** (2), 51-69.
- PALLARY P., 1920 - Descriptions d'une nouvelle cinquantaine de mollusques terrestres nouveaux du Nord-Ouest de l'Afrique. *Bulletin de la Société d'histoire naturelle de l'Afrique du nord*, **11** (2), 18-34.
- PALLARY P., 1926 - Compléments à la faune malacologique de la Berbérie. *Journal de Conchyliologie*, **70** (1), 1-50.
- PALLARY P., 1928 - Complément à la faune malacologique de la Berbérie (suite). *Journal de Conchyliologie*, **71** (3), 197-277.
- PEDLEY H.M., 1990 - Classification and environmental models of cool freshwater tufas. *Sedimentary Geology*, **68** (1-2), 143-154.
- PEDLEY H.M., 2003 - Sedimentology of Quaternary perched springline and paludal tufas: criteria for recognition, with example from Guadalajara Province, Spain. *Sedimentology*, **50**, 23-44.
- PEDLEY H.M., 2009 - Tufas and travertines of the Mediterranean region: a testing ground for freshwater carbonate concepts and developments. *Sedimentology*, **55**, 221-246.
- PENTECOST A., 1995 - The quaternary travertine deposits of Europe and Asia Minor. *Quaternary Science Reviews*, **14** (10), 1005-1028.
- PIGATI J.S., RECH J.A. & NEKOLA J.C., 2010 - Radiocarbon dating of small terrestrial gastropod shells in North America. *Quaternary Geochronology*, **5**, 19-32.
- PREECE R.C., 1991 - Mapping snails in time: the prospect of elucidating the historical biogeography of the European malacofauna. *Proceedings of the Tenth International Malacological Congress, Tübingen*, **27**, 477-479.
- PUISSÉGUR J.J., 1976 - *Mollusques continentaux quaternaires de Bourgogne*. Mémoires Géologiques de l'Université de Dijon, **3**, Doin, Paris, 241 p.
- REIMER P.J., BARD E., BAYLISS A., BECK J.W., BLACKWELL P.G., BRONK RAMSEY C., BUCK C.E., CHENG H., EDWARDS R.L., FRIEDRICH M., GROOTES P.M., GUILDERSON T.P., HAFLIDASON H., HAJDAS I., HATTÉ C., HEATON T.J., HOFFMANN D.L., HOGG A.G., HUGHEN K.A., KAISER K.F., KROMER B., MANNING S.W., NIU M., REIMER R.W., RICHARDS D.A., SCOTT E.M., SOUTHON J.R., STAFF R.A., TURNEY C.S.M. & VAN DER PLICHT J., 2013 - IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal B.P. *Radiocarbon*, **55** (4), 1869-1887.
- RHOJJATI A., CHEDDADI R., TAÏEB M., BAALI A. & ORTU E., 2010 - Environmental changes over the past 29,000 years in the Middle Atlas (Morocco): a record from Lake Ifrah. *Journal of arid environments*, **74** (7), 737-745.
- RHOJJATI A., NOURELBAÏT M., BENKADDOUR A., DAMNATI B., BAALI A., TAÏEB M., DECOBERT M., MALEK F. & CHEDDADI R., 2012. Significations paléoenvironnementales des dépôts du remplissage holocène du lac Ifrah (Moyen Atlas, Maroc). *Quaternaire*, **23** (3), 241-252.
- ROBERTS N., BRAYSHAW D., KUZUCUOĞLU C., PEREZ R. & SADORI L., 2011 - The mid-Holocene climatic transition in the Mediterranean: causes and consequences. *The Holocene*, **21** (1), 3-13.
- ROBERTS N., WOODBRIDGE J., PALMISANO A., BEVAN A., FYFE R. & SHENNAN S., 2019 - Mediterranean landscape change during the Holocene: Synthesis, comparison and regional trends in population, land cover and climate. *The Holocene*, **29** (5), 923-937.
- ROHLING, E. J., MARINO, G. & GRANT, K. M. 2015 - Mediterranean climate and oceanography, and the periodic development of anoxic events (sapropels). *Earth-Science Reviews*, **143**, 62-97.
- ROUR E., CHAHLAOUI A. & VAN GOETHEM J., 2002 - Etat actuel des connaissances de la malacofaune terrestre du Maroc. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique, Biologie*, **72**, 189-198.
- SEDDON M., HOLYOAK D. & APARICIO M.T., 1994 - Taxonomy of five species of *Helicopsis* (Helicopsis) from Morocco (Gastropoda: Helicoidea). *Journal of Conchology*, **35**, 45-66.
- SEDDON M. & APARICIO M.T., 1998 - Problematic taxa from Morocco-the status of '*Helix argonautula*' Webb & Berthelot, 1833, '*Helix renati*' Dautzenberg, 1894 and '*Xeroleuca antoinei*' Pallary, 1936. *Journal of Conchology*, **36**, 19-29.
- SEDDON M., 1999 - Hotspots of Molluscan biodiversity: use of presence/absence data for prioritisation of conservation management in North Africa. *Bulletin of the Malacological Society of London*, **33**, 6-8.
- TAYBI A.F., MABROUKI Y., GHAMIZI M. & BERRAHOU A., 2017 - The freshwater malacological composition of Moulouya's watershed and Oriental Morocco. *Journal of Materials and Environmental Science*, **8** (4), 1401-1416.
- TAYLOR V.K., BARTON R.N.E., BELL M., BOUZOUGGAR A., COLLCUTT S., BLACK S. & HOGUE J.T., 2011 - The Epipalaeolithic (Iberomaurusian) at Grotte des Pigeons (Taforalt), Morocco: a preliminary study of the land Mollusca. *Quaternary International*, **244** (1), 5-14.
- TAYLOR V.K. & BELL M., 2017 - Land mollusk middens. In Allen M.J., (Ed), *Molluscs in Archaeology. Methods, approaches and applications*. Oxbow Books, Oxford, 195-212.
- VAN DAMME D., 1984 - *The freshwater Mollusca of northern Africa: distribution, biogeography and palaeoecology*. Junk Publisher, Dordrecht, 163 p.

VAN DAMME D., GHAMIZI M., SOLIMAN G., MCIVOR A. & SEDDON M., 2010 - The status and distribution of freshwater molluscs. In N. Garcia, A. Cuttelod & Abdul Malak D. (ed.), *The Status and Distribution of Freshwater Biodiversity in Northern Africa*, IUCN, Gland, 29-49.

WELTER-SCHULTES F.W., 2012 - *European non-marine molluscs, a guide for species identification*. Planet Poster, Göttingen, 760 p.

ZIELHOFER C., BUSSMANN J., IBOUHOUTEN H. & FENECH K., 2010 - Flood frequencies reveal Holocene rapid climate changes (Lower Moulouya River, northeastern Morocco). *Journal of Quaternary Science*, **25** (5), 700-714.

ZIELHOFER C., FLETCHER W.J., MISCHKE S., DE BATIST M., CAMPBELL J.F., JOANNIN S., TJALLINGH R., ELHAMOUTIN., JUNGUNGERA., STELE A., BUSSMANN J., SCHNEIDER B., LAUER T., SPITZER K., STRÜPLER M., BRACHERT T. & MIKDAD A., 2017 - Atlantic forcing of Western Mediterranean winter rain minima during the last 12,000 years. *Quaternary Science Reviews*, **157**, 29-51.