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STUDIES ON THE PLEISTOCENE OF LATIUM: UNDERSTANDING THE GLACIO-EUSTATIC FORCING ON THE AGGRADATIONAL SUCCESSIONS OF THE TYRRHENIAN SEA MARGIN OF CENTRAL ITALY

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ABSTRACT: The studies conducted by Francesco Paolo "Antonello" Bonadonna in the area of Rome during the 1960s laid the basis for development of the first complete chronostratigraphy scheme for the Middle-Upper Pleistocene of this region. This scheme reported the succession of alternating erosional phases and transgressive series, and their correlation with the limited number of glacial-interglacial cycles known at that time, highlighting the implicit glacio-eustatic trigger of the sedimentary process. Besides describing the observations and the inferences that allowed Bonadonna to develop the methodological approach to the study of the stratigraphy of this region, in the present paper I will also show how, starting from these basic principles, the modern chronostratigraphic framework of glacio-eustatically controlled aggradational successions used today to describe the stratigraphy of the Tiber basin has been developed.

Keywords: chronostratigraphy, Rome, aggradational successions, glacio-eustasy, erosive phases, transgressive series.

1. INTRODUCTION

In the years 1963-1970, Francesco Paolo (Antonello for all who have worked with him) Bonadonna published a series of works under the collection title "Studi sul Pleistocene del Lazio", which laid the basis of the modern approach to the study of the glacio-eustatic forcing on the sedimentation processes in the area of Rome. Results of these studies were eventually summarized in 1972 in the paper "A scheme of Pleistocene chronology for the Tyrrhenian side of central Italy", by Ambrosetti, Azzaroli, Bonadonna and Follieri, providing the first detailed chronostratigraphic scheme for this region. This scheme was based on the identification of a series transgressive series separated by erosional phases, which were correlated with the limited number of glacial periods known at that time, highlighting the implicit glacio-eustatic trigger of the sedimentary process. The erosional phases in this scheme are those previously identified by Blanc and other authors, who named them after the main consular roads in the northern area of Rome, where their observations were conducted and type sections were described: Cassia, Flaminia, Nomentana. A synthesis of this broader scheme is provided in Table 1 of the present paper, where it is compared with an up-to-date chronostratigraphy for the area of Rome (Luberti et al., 2017). Indeed, this scheme provided the basis of the chronostratigraphic and paleoclimatic studies that many scholars, among them the author of the present contribution, have conducted in the area of Rome since the early 1990s.

In this paper, I will describe the observations and the inferences that allowed Bonadonna to develop the methodological approach to the study of the stratigraphy of this region. I will show also how, starting from these basic principles, the modern chronostratigraphic framework of glacio-eustatically controlled aggradational successions used today to describe the stratigraphy of the Tiber basin has been developed.

2. DIATOMITIC BASINS AND VOLCANIC LAYERS: CHRONOSTRATIGRAPHICALLY CONSTRAINED PALEOCLIMATIC ARCHIVES

In his early works, Bonadonna (1963, 1964, 1965) investigated three diatomitic basins located to the north of Rome, within the volcanic region of the Monti Sabatini district, highlighting the chronostratigraphic constraints

Luberti et al. (2017) MIS GT	AGE (ka)	SEDIMENTARY UNIT	VOLCANIC UNIT	Conato et al. (1980)	Ambrosetti et al. (1972) EROSIVE PHASE	TRANSGRESSIVE SERIES
MIS 1 T-I	15 – Present 14.6-13.6	**Modern Tiber Fm**				
2.2	17				PONTINIAN (.058) - Würm I	
6.2/5.1 T-II MIS 5.1 MIS 5.3 MIS 5.5	133-79 130 79 97 122	**Epi-Tyrrhenian Fm** Quadrato sub-unit Tenuta Campo Selva sub-unit Cava Rinaldi sub-unit	**Baccano Lower Unit** 131±2	Neo-Tyrrhenian Fm (MIS 5c/a) Vitinia Fm Eu-Tyrrhenian Fm (MIS 5e)		3rd Strombus raised beach (90) 2nd Strombus raised beach (127) 1st Strombus raised beach (177 >200)
6.2	133					
8.4/7.1 T-III	266-194 243	**Vitinia Fm**				
8.4	266					
8.6/8.5	295-287	**Via Mascagni succession**	**TGS: Tufo Giallo di Sacrofano** 285±2		OSTIAN (~ .230) - Riss II	RIANIAN (280)
8.6	295					
10.4/9.3 T-IV 10.2	357-328 337 340	**Aurelia Fm**		Aurelia Fm (MIS 9)		
10.4	357		**Villa Senni Eruptive Cycle:** 365±4 **Tufo Lionato-Pozzolanelle**			
12.2/11.3 T-V	430-400 419	**San Paolo Fm**	**Pozzolane Nere** 407±2 **Vico** α/β 410±2 - 416±6	San Cosimato Fm (MIS 15)		
12.2	434		**Tufo Rosso a Scorie Nere** 449±2 **Pozzolane Rosse** 456±3		NOMENTANAN (< .430) - Riss I	
13.2/13.1 14.2/13.3 T-VI	510 - 481 536 - 524 533	**Valle Giulia Fm**	**Fall A** 498±2 **Grottarossa Pyroclastic Seq.** 510±4 **Tufo Giallo di Prima Porta** 516±1 **Tufo del Palatino** 533±2			PARIOLIAN
14.2	536				FLAMINIAN (~ .700) - Mindel	
15.2/15.1 T-VIIB	582-573 580	**Fosso di Malafede succession**	**FAD 1** 585±4			
15.2	582					
16.4/15.3 T-VIIA 16.2 16.4	650-594 621 628 658	**Santa Cecilia Fm**	**Santa Cecilia Eruption Unit** 611±3 **Vigna Murata Eruption Unit** 649±4	Ponte Galeria Fm Salmon sand (MIS 21)		
18.2/17.3 T-VIIIB	718-688 712	**Ponte Galeria 2 Fm** PG2B Unit *Venerupis senescens* clay Gravel and sand with frequent cross-laminations		*Venerupis senescens* clay		
18.2	718					
18.4/18.3 T-VIIIA	754-729 745	PG2A Unit Middle clay Gravel and sand with frequent cross-laminations	**Ponte Galeria Eruption Unit** 758±8	Gravel and sand with frequent cross-laminations		GALERIAN
18.4	754					
20.2-19.3 T-IX	793-782 790	**Ponte Galeria 1 Fm** *Helicella* clay River conglomerate	**Paleotiber Succession:** **Unit D** 783±13 **Unit C** 796±9 **Unit B** 800±9 **Unit A** 802±6	*Helicella* clay River conglomerate		
20.2	793				CASSIAN (~ 1.000) - Günz (?)	
22.2/21.5 T-X	871-858 866	**Monte Ciocci Fm** Monte delle Piche Unit Monte Ciocci Unit		Monte delle Piche Series		
22.2	871					
56/55	1628-1585	**Monte Mario Fm** Clays and *Cerastoderma*-bearing sands Yellow sands with silty intercalations		Monte Mario Series		CALABRIAN (~ 1.900)
58/57	1660-1628	Yellow sands with "panchina" *Arctica islandica* sands Farneto silts				
					ACQUATRAVERSAN (> 2.500 <3.400) - Donau I (?)	
ZANCLEAN	3810-2700	**Marne Vaticane Fm**				

Tab. 1 - The chronostratigraphic scheme by Ambrosetti et al. (1972) based on alternating erosive phase and transgressive series (on the right, in brackets: ages in ka) is compared to the modern chronostratigraphic scheme based on $^{40}Ar/^{39}Ar$ ages of volcanic products and correlation of aggradational successions with sea-level rise during glacial terminations (to the left). The earliest chronostratigraphic scheme providing tentative correlation with the oxygeen isotope curve proposed by Conato et al. (1980) is also shown.

First column in the scheme by Luberti et al. (2017) provides correlation with marine isotopic stage (MIS; first row) and Glacial Termination (T-, second row). Numbering of isotopic stages after Bassinot et al. (1994). Second column provides ages for the isotopic intervals reported in first column (first row) after Bassinot et al. (1994), and ages for glacial terminations (second row), after astrochronocalibration by Lisiecki and Raymo (2005), with the exception of the last glacial termination (T-I) for which is reported the age of Melt-water pulse 1A after Stanford et al. (2006). $^{40}Ar/^{39}Ar$ ages (ka) of the eruptive cycles and eruptive units after Gaeta et al. (2016) and Marra et al. (2016c) and references therein, are also provided in this column. The third column provides names of the Formations and of the successions (see also Fig. 1) corresponding to the aggradational successions. The fourth and fifth columns provide names of the volcanic units and their $^{40}Ar/^{39}Ar$ ages in ka.

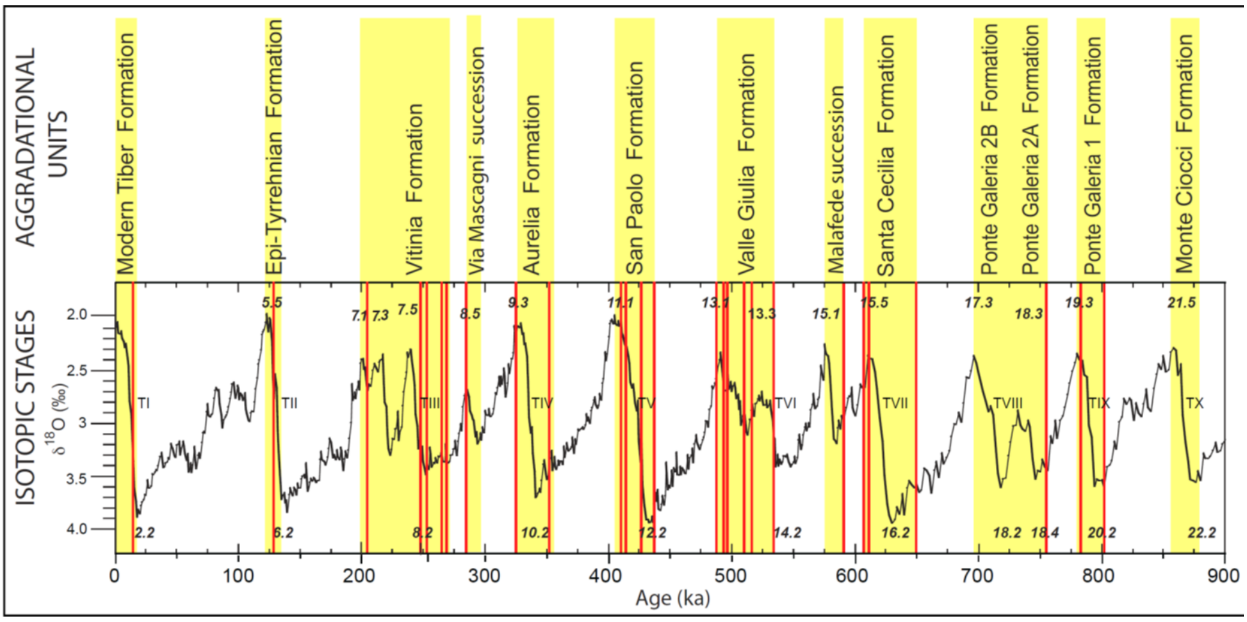

Fig. 1 - A series of geochronologically constrained aggradational phases (yellow vertical boxes), corresponding to as many formally introduced sedimentary successions (Formation) in the area of Rome, has been directly correlated with post-glacial sea-level rises (glacial terminations TI - TX) and the corresponding marine isotopic stages (MISs). Vertical red lines are the age constraints derived by the $^{40}Ar/^{39}Ar$ dating of the volcanic deposits intercalated within the aggradational units of the Paleotiber River; each colored box individuates a period of sea-level rise that accounts for the deposition of the sedimentary successions in the coastal area of Rome. Minor aggradational phases linked with smaller sea-level oscillations (sub-stages of the $\delta^{18}O$ record) are given the rank of 'succession'. Oxygen isotopes curve after Lisiecki and Raymo (2005); stage numbering after Bassinot et al. (1994).

provided by the occurrence of the pyroclastic deposits intercalated in these lacustrine successions. He was among the first scholars to understand the opportunity provided by the prolonged and intense explosive volcanic activity of this region to date the geologic events that occurred during the Middle Pleistocene (i.e., a tephrochronologist *ante litteram*). On the basis of identification of known eruptive units interbedded with the sedimentary deposits, he recognized the chronological order of the three lacustrine successions even in the absence of direct stratigraphic evidence. Moreover, he framed the deposition of the sediments within the embryonic scheme of alternating erosive and depositional phases outlined at that time, and he discussed their paleoclimatic implications, forming a prelude to what would eventually become the modern methodological approach to the study of the interplay between glacioeustasy and sedimentation in the area of Rome. Finally, he was a pioneer of the radiometric dating of the volcanic products, aimed at providing absolute ages for the sedimentary and volcanic successions and highlighting the relationships with the glacial/interglacial periods, by developing with Giulio Bigazzi the "fission-track" dating method (Bonadonna & Bigazzi, 1968, 1970).

Hereby, I would like to summarize the conclusions of the 1965 paper on the chronostratigraphy of the Valle dell'Inferno diatomitic basin of Riano and its relationships with the volcanic deposits cropping out along the Via Flaminia in Cava Nera Molinario. Bonadonna observed the strong differences in elevation affecting the contact between the earliest volcanic deposits, including the "*vacuolar yellow lithoid tuff*" (=Tufo Gialo della Via Tiberina and Tufo Giallo di Prima Porta) and the "*lower granular tuff*" (=Tufo del Palatino) (Karner et al., 2001a), and the marine-brackish substrate of Calabrian and Sicilian age, coming to the conclusion that "*the lithoid tuff filled pre-existing valleys and leveled the zone*". Therefore, he associated the occurrence of this erosive phase and the concurrent emplacement of the tuff with the Flaminian cold period, following nomenclature and previous observations made in this area by Blanc et al. (1955). He also noted that "*the whole area was finally remodelled by an exceptionally erosive phase, which removed, sometimes completely, the continental or volcanic sediments which had deposited, up to then, on the Calabrian or Sicilian sand. The "black pumice tuff"* (=Tufo Rosso a Scorie Nere Sabatino, Mattias and Ventriglia, 1970; Table 1) *poured as a mudflow on this deeply marked zone.*" Consistent with Blanc et al.'s (1955) observation that the eruption of the "*black pumice tuff*" was ascribed to a time just preceding the Nomentano cold period, Bonadonna noted that it was affected by strong erosion, "*since very few outcrops are left in place",* and deduced that the lake of Valle dell'Inferno (whose diatomitic deposits unconformably overlie the Tufo Rosso a Scorie Nere) "*began to exist certainly after the erosion* (...) *that we can ascribe to the Nomentano*".

In Figure 1 I have depicted the stratigraphic schemes of the two sites investigated by Bonadonna (1965), updated with the modern geochronologic constraints provided by $^{40}Ar/^{39}Ar$ dating of the volcanic products (Marra et al., 2018), which allow correlation of the erosional and aggradational phases with the sea-level oscillations linked with the glacial/interglacial phases, as detected on the marine oxygen isotope records. These schemes show how much of this correlative method is inherited from the original approach employed by Bonadonna to assess the interplay between climate oscillations and erosional/depositional phases. Indeed, he lacked only a reliable dating method to assess the absolute age of the recognized events.

Today, we know that two distinct eruptions emplaced the Tufo Giallo della Via Tiberina and the Tufo Giallo di Prima Porta (previously identified as a single volcanic unit corresponding to the "vacuolar lithoid tuff", later named Colata Piroclastica inferiore di Sacrofano by De Rita et al., 1993) at 546 ±3 and 516 ±1 ka, respectively (Karner et al., 2001a; Marra et al., 2014a; 2017a). Moreover, we know that the previously named "Peperino della Via Flaminia" (the "lower granular tuff" by Bonadonna, 1965) is actually a distal deposit of the Tufo del Palatino erupted by the Colli Albani volcanic district 533 ±2 ka (Karner et al., 2001a). Finally, we have very precise ages for the Tufo Rosso a Scorie Nere sabatino (hereby TRSN: 452 ±2 ka, Karner et al., 2001a) and for a series of volcanic units constraining the time of deposition of the two aggradational successions emplaced during sea-level rise of MIS 13 and MIS 11: the Valle Giulia and the San Paolo Formations (Karner & Marra, 1998) (Figure 1). In the following section I will describe the basic principles of the methodological approach based on the aggradational succession sedimentary model, and afterwards I will show how it applies to the stratigraphic setting of Riano and Cava Nera Molinario discussed by Bonadonna (1965).

3. AGGRADATIONAL SUCCESSIONS: A METHODOLOGICAL APPROACH DEEPLY ROOTED IN PREVIOUS STUDIES

Following the criterion by which sea-level oscillations linked with glacial cycles controlled the alternating erosional and depositional phases within the Tiber River basin and its delta, Karner & Marra (1998) have introduced the concept of the "aggradational section". This is defined as the stratigraphic record of a complete glacially forced sea-level oscillation in a coastal area, as represented by a basal erosive surface, progressively excavated as a consequence of coastline regression and lowering of sea level during glacial periods, covered by a fining-upward sequence of clastic sediments (namely the aggradational succession), rapidly deposited during sea-level rise in response to deglaciation. Generally, the aggradational successions recognized in Rome display a gravel and sand layer at the base of each complete section. This basal coarse-grained deposit is followed by a relatively thin sand horizon, which grades rapidly upward into a several meters thick package of silt and clay deposits that represents the largest portion of the aggradational succession.

A large number of $^{40}Ar/^{39}Ar$ ages for volcanic layers intercalated within the sedimentary deposits in the coastal area of Rome allowed the verification and refinement of the correlation with the oxygen isotope timescale (Karner & Renne, 1998; Marra et al., 1998; Karner et al., 2001b; Florindo et al., 2007) (Figure 1). Later on, Marra et al. (2008; 2016a) developed a sedimentary model in which the abrupt transition from gravel to clay within the aggradational successions of the Tiber River represents a good proxy for the glacial termination.

The conceptual sedimentary model has been tested and formulated on the last deglaciation cycle, i.e., the glacial termination I and Holocene, for which a robust radiocarbon chronological framework is available. Specifically, ^{14}C age constraints on the sedimentary record deposited within the valley and in the coastal plain of the modern Tiber River (Marra et al., 2008; 2013; 2016a) have shown that the deposition of gravel marked a unique time in the depositional history of the river, occurring during a ~7 ka interval between the end of the Last Glacial Maximum (LGM 21-18 ka) and the onset of the Last Glacial Termination (LGT ~14 ka). Indeed, transportation by the Tiber River of gravel with grain size >5 cm required exceptional hydrologic conditions that have not been repeated during the Holocene. While continuous transportation of coarse material occurs during the regressive phase, this material cannot accumulate within the fluvial incision or within the coastal plain, as a consequence of the continued regression of the coastline, causing its removal and redeposition seaward, while the base level of the sedimentary record is progressively deepened. Conditions for rapid accumulation of coarse gravel typically exist only

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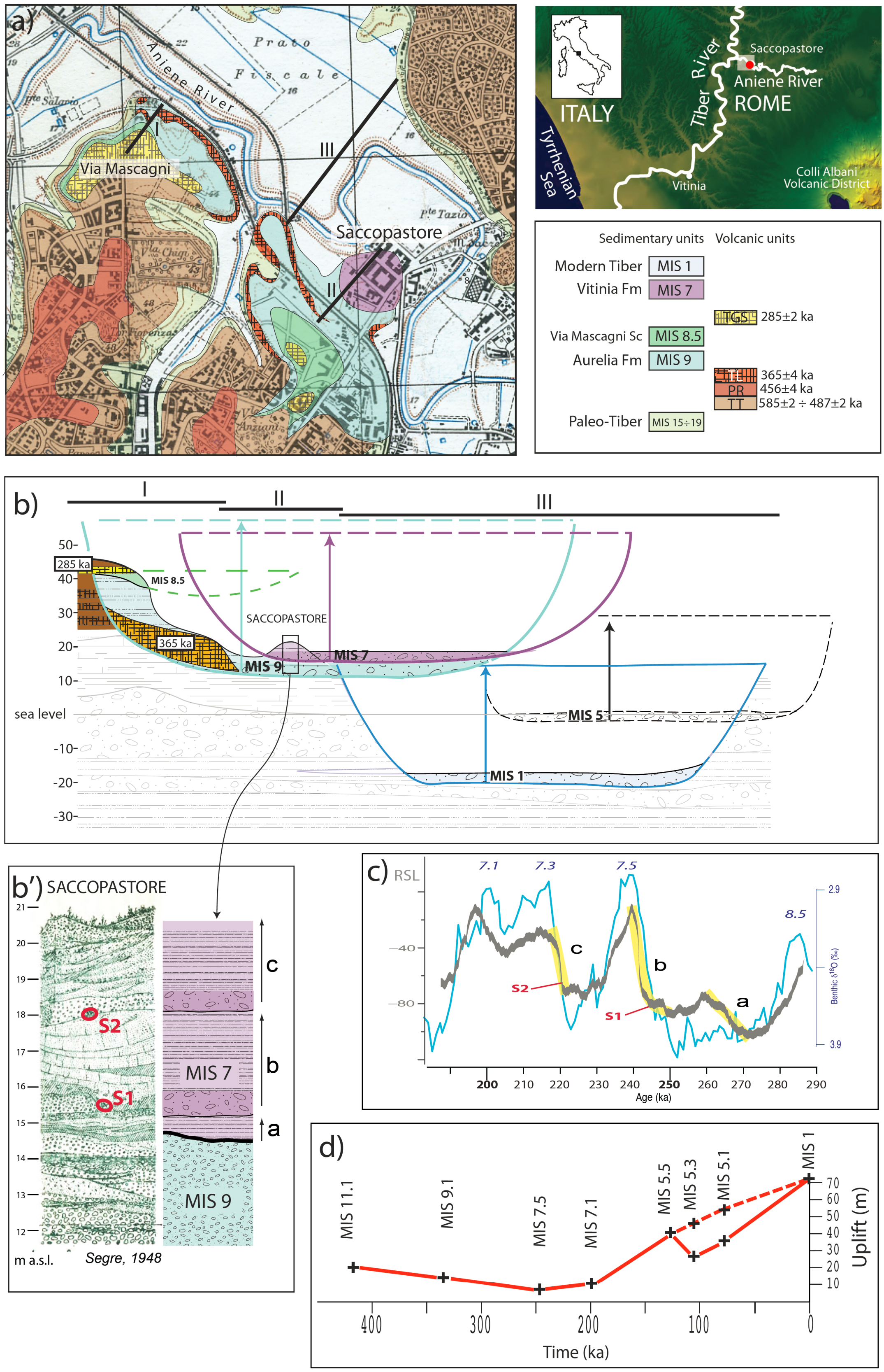
Fig. 2 a) Geologic map of the Aniene Tiber valley north of Rome (from Marra et al., 2015); TGS: Tufo Giallo di Sacrofano, TL: Tufo Lionato, PR: Pozzolane Rosse, TT: pyroclastic products of the Early Tuscolano artemisio phase and Monti Sabatini volcanic district; I-II-III trace of composite cross-section shown in inset b; b) Reconstruction of geometry and elevation of the sedimentary bodies of aggradational successions deposited during sea-level rises of MIS 9, MIS 8.5 and MIS 7, based on geologic remnants of the original deposits including the basal gravel layer, and comparison with that of the last aggradational succession of MIS 1, based on borehole data. An elevation gain of ca. 40 m is observed between the reconstructed alluvial plains of the deposits correlated with MIS 9 and MIS 7 with respect to that of MIS 1, consistent with the occurrence of the regional uplift since 200 ka (see inset d); consequently, an intermediate elevation around present day sea -level iusexpected for the basal gravel layer of the MIS 5.5 aggradational succession.
b') Stratigraphy of Saccopastore reporting the position of the two Neanderthal skulls (S1 and S2) and interpreted stratigraphy, showing the occurrence of three MIS 7 aggradational phases (a, b, c) erosionally above the basal gravel layer of the Aurelia formation (MIS 9); c) Curve of global relative sea level (RSL, Grant et al., 2014) in the time span 290-200 ka, showing the occurrence of three consecutive peaks (a, b, c, highlighted by the thick yellow lines) at around 270 ka, 245 ka, and 220 ka. The Oxygen isotope curve (Lisiecki and Raymo, 2005) for the same time span is also reported, showing that the three aggradational successions recognized in Saccopastore (a, b, c) are correlated with the three sea-level rises occurring during MIS 7, providing indirect ages of 245 ka and 220 ka for the two skulls, S1 and S2, respectively; d) Uplift curve for the coastal sector of Rome; the dashed line represents an alternative hypothesis based on similar sea-levels than in the present for MIS 5.3 and 5.1 (see Marra et al., 2016b, for a discussion).


a)
Aniene River
Prato
Fiscale
Via Mascagni
Saccopastore
I
II
III
Saccopastore
Aniene River
ROME
River
Tiber
ITALY
Tyrrhenian Sea
Vitinia
Colli Albani Volcanic District
Sedimentary units
Volcanic units
Modern Tiber MIS 1
Vitinia Fm MIS 7
TGS 285±2 ka
Via Mascagni Sc MIS 8.5
Aurelia Fm MIS 9
TL 365±4 ka
PR 456±4 ka
TT 585±2 ÷ 487±2 ka
Paleo-Tiber MIS 15÷19
b)
I
II
III
285 ka
MIS 8.5
SACCOPASTORE
365 ka
MIS 9
MIS 7
MIS 5
MIS 1
sea level
b') SACCOPASTORE
S2
S1
MIS 7
MIS 9
c
b
a
m a.s.l.
Segre, 1948
c) RSL
7.1
7.3
7.5
8.5
S2
S1
c
b
a
Benthic δ18O (‰)
Age (ka)
d)
MIS 11.1
MIS 9.1
MIS 7.5
MIS 7.1
MIS 5.5
MIS 5.3
MIS 5.1
MIS 1
Uplift (m)
Time (ka)

during deglaciation phases due to the combination of several factors such as the increased sediment supply to the Tiber drainage basin, caused by fast melting of Apennine glaciers releasing a large amount of clastic material, combined with the low sea level causing a steeper gradient, and hence greater river transport capacity. These conditions would have worked in concert during the 18-14 ka interval, until the accelerated sea-level rise during the LGT led to a rapid drop in capacity of transport by the Tiber and, consequently, to the start of sandy clay deposition and filling of the fluvial incisions.

4. PRACTICAL APPLICATION OF THE AGGRADATIONAL SUCCESSION METHOD

Due to the processes that guide their formation, aggradational successions are intrinsically discontinuous records of ten major units deposited during the major glacial cycles spanning MIS 21 thorough MIS 1 by the (Paleo) Tiber River and its tributaries in the near-coastal to coastal area, plus several minor successions associated with the more pronounced sea-level oscillations within the same isotopic stage (sub-stages). The corresponding sedimentary deposits have been designated by formal formation names, as shown in the chronostratigraphic scheme of Table 1 (Luberti et al., 2017). These sedimentary successions are variably exposed along the banks of the hills shaped from an original pyroclastic plateau, eroded by fluvial incisions of the Tiber River and its tributaries in consequence of the interplay between glacio-eustasy and a discontinuous regional uplift that affected the Tyrrhenian Sea margin of central Italy in the last 800 ka (Karner et al., 2001b; Marra et al., 2016b). Therefore, the stratigraphic record of each glacio-eustatic cycle occurs at a different elevation, depending on the absolute sea-level during each glacial/interglacial period and on the amount of uplift experienced since their deposition, thus offering a further geometric criterion for its identification. This is the case at the archaeological site of Saccopastore, where two Neanderthal skulls were recovered in the years 1929-35 within two gravel layers at the base of a fining-upward succession cropping out in the Aniene River Valley north of Rome (Sergi, 1929; Breuil & Blanc, 1935). An age of ca. 130 ka was initially estimated for the human individuals, based on attribution of the deposit to a fluvial terrace of the last interglacial stage (MIS 5e) (Blanc, 1939, 1946, 1948; Segre, 1948), whereas an age as young as 80 ka was subsequently proposed (Manzi et al., 2001), due to the occurrence of cold climate vegetal species (leaves) within the sedimentary record.

However, by simply applying the basic principles of the aggradational succession sedimentary model, Marra et al. (2017b) recognized that the gravel layers marked a glacial termination rather than an interglacial period, consistent with the cold paleoclimatic indicators of the associated clay section. Moreover, their elevation excluded an age within MIS 5, while it matched that pertaining to the MIS 7 aggradational succession of the Vitinia Formation (250-210 ka, Karner & Marra, 1998; Marra et al., 2016a), consistent with stratigraphic relationships between the Saccopastore sedimentary deposit and the well-constrained MIS 9 and MIS 8.5 deposits of the Aurelia Formation and of the Via Mascagni succession (350 through 285 ka, Marra et al., 2017b) cropping out in this area (Figure 2).

The composite cross-section of Figure 2 shows that the two gravel layers where the Neanderthal skulls (S1 and S2 in Figure 2b) were recovered occur above a third, thicker gravel layer which was already identified as part of an older succession, due to the presence of Middle Pleistocene faunal remains (i.e., an archaic form of *Elephas* (=*Palaeoloxodon*) *antiquus*; Breuil & Blanc, 1936). The stratigraphic relationship of this gravel with the pyroclastic-flow deposit of Tufo Lionato (365 ±4 ka, Marra et al., 2009) allows its identification as the basal gravel layer of the MIS 9 aggradational succession (Figure 2b), the sedimentary deposits of which (Aurelia Formation) crop out extensively in this area (Figure 2a). Therefore, the upper gravel layers constitute the basal coarse portion of the successive aggradational succession of MIS 7 (Figure 2b), which is embedded within the eroded deposits of the previous one, and occurs at the same elevation, consistent with the lack of regional uplift in the time span 400-200 ka (see uplift curve by Marra et al., 2016b in Figure 2d). In contrast, the following aggradational successions must display a base level at progressively lower elevation, due to the ca. 60 m intervening uplift in the time span 200 ka - Present (Figure 2d). Consistently, the basal gravel layer of the MIS 1 aggradational succession is found at ca. 15 m below the present sea level in the boreholes drilled within the alluvial filling of the Aniene Valley (Marra et al., 2015), ca. 35 m lower than the equivalent gravel layer of MIS 7 (Figure 2b). Similarly, the equivalent gravel layer of MIS 5 should occur at intermediate elevation, around the present sea-level (Figure 2b), ruling out the hypothesis that the gravel occurring between 15 and 19 m a.s.l. in Saccopastore may have been emplaced during the penultimate glacial termination of MIS 5.5. Correlation with MIS 7 for the upper gravel beds of Saccopastore is further supported by re-determination of a upper molar of

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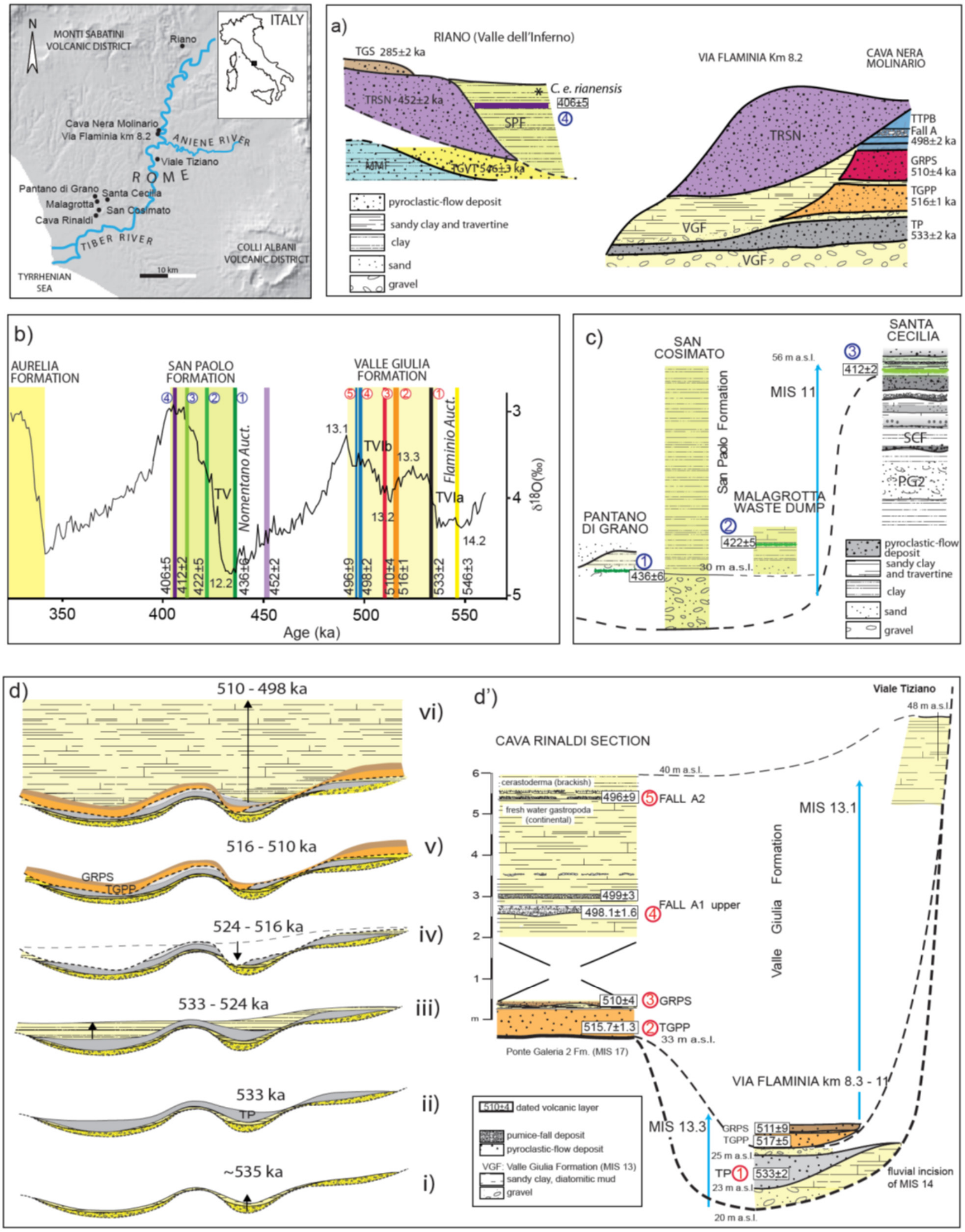
Fig. 3 - a) Stratigraphic schemes of the localities along Via Flaminia described by Bonadonna (1965), updated with the geochronologic constraints providing correlation (b) with the aggradational successions of MIS 13 and MIS 11 (Valle Giulia and Span Paolo Formations: VGF and SPF) (from Marra et al., 2018). c - d) Composite cross-sections showing the aggradational sections of the Valle Giulia and San Paolo Formation cropping out in distinct locality of the Tiber valley, with the intercalated volcanic layers whose 40Ar/39Ar ages (numbered in circles) allow to reconstruct the time of aggradation and to compare it with the d18O curve in inset b; d') Age constraints to the reconstructed sedimentary history of the Valle Giulia Formation show excellent match with the two consecutive sea-level rises during MIS 13 (see text for comments and explanations).

PG2: Ponte Galeria 2 Formation, SCG: Santa Cecilia Formation; TGVT: Tufo Giallo della Via Tiberina, TP: Tufo del Palatino, TGPP: Tufo Giallo di Prima Porta, GRPS: Grottarossa Pyroclastic Sequence; TTPB: Tufi Terrosi con Pomici Bianche, TRSN: Tufo Rosso a Scorie Nere, TGS: Tufo Giallo di Sacrofano.



N
MONTI SABATINI VOLCANIC DISTRICT
Riano
ITALY
Cava Nera Molinario
Via Flaminia km 8.2
ANIENE RIVER
Viale Tiziano
ROME
Pantano di Grano
Santa Cecilia
Malagrotta
San Cosimato
Cava Rinaldi
TIBER RIVER
COLLI ALBANI VOLCANIC DISTRICT
10 km
TYRRHENIAN SEA
a)
RIANO (Valle dell'Inferno)
TGS 285±2 ka
TRSN 452±2 ka
C. e. rianensis
406±5
SPF
MMF
TGVT 546±3 ka
pyroclastic-flow deposit
sandy clay and travertine
clay
sand
gravel
VIA FLAMINIA Km 8.2
CAVA NERA MOLINARIO
TRSN
TTPB
Fall A
498±2 ka
GRPS
510±4 ka
TGPP
516±1 ka
TP
533±2 ka
VGF
b)
AURELIA FORMATION
SAN PAOLO FORMATION
VALLE GIULIA FORMATION
Nomentano Auct.
Flaminio Auct.
TV
TVIb
TVIa
13.1
13.3
13.2
12.2
14.2
406±5
412±2
422±5
436±6
452±2
496±9
498±2
510±4
516±1
533±2
546±3
δ18O(‰)
Age (ka)
350
400
450
500
550
c)
SAN COSIMATO
San Paolo Formation
56 m a.s.l.
MIS 11
SANTA CECILIA
412±2
SCF
PG2
PANTANO DI GRANO
436±6
MALAGROTTA WASTE DUMP
422±5
30 m a.s.l.
pyroclastic-flow deposit
sandy clay and travertine
clay
sand
gravel
d)
510 - 498 ka
vi)
516 - 510 ka
v)
GRPS
TGPP
524 - 516 ka
iv)
533 - 524 ka
iii)
533 ka
ii)
TP
~535 ka
i)
d')
CAVA RINALDI SECTION
Viale Tiziano
48 m a.s.l.
40 m a.s.l.
cerastoderma (brackish)
496±9
FALL A2
fresh water gastropoda (continental)
MIS 13.1
Valle Giulia Formation
499±3
498.1±1.6
FALL A1 upper
510±4
GRPS
515.7±1.3
TGPP
33 m a.s.l.
Ponte Galeria 2 Fm. (MIS 17)
VIA FLAMINIA km 8.3 - 11
510±4 dated volcanic layer
pumice-fall deposit
pyroclastic-flow deposit
VGF: Valle Giulia Formation (MIS 13)
sandy clay, diatomitic mud
gravel
MIS 13.3
GRPS 511±9
TGPP 517±5
25 m a.s.l.
TP 533±2
23 m a.s.l.
20 m a.s.l.
fluvial incision of MIS 14

Dama dama tiberina, part of the faunal assemblage recovered at this location hosted at the Museo Pigorini in Rome (Marra et al., 2017b, Salari et al., 2018), a fallow deer sub-species whose occurrence in peninsular Italy is limited to MIS 8.5-MIS 7, and was replaced by *Dama dama dama* during MIS 5.5 (Di Stefano and Petronio, 1997; Marra et al., 2018). Combining all these observations, Marra et al. (2017b) suggested that the two gravel layers hosting the two skulls (S1 and S2) correspond to the two sea-level rises of MIS 7.5 and MIS 7.3, resulting into a pair of consecutive aggradational successions (b and c in Figure 2c), preceded by deposition of a fine-sized layer (a) triggered by a moderate, early sea-level rise, as seen in the Relative Sea Level (RSL) curve of Grant et al. (2014).

5. THE VALLE GIULIA AND SAN PAOLO FORMATIONS CROPPING OUT IN VIA FLAMINIA AND RIANO

Another practical application of the conceptual model refres to the case of the Valle Giulia and San Paolo Formations. In agreement with Bonadonna's (1965) observations, the stratigraphic scheme of Riano in Figure 3a shows that the Tufo Giallo della Via Tiberina ("vacuolar lithoid tuff") rests above the eroded marine substrate (Monte Mario Formation, MMF, Bonadonna, 1968). Consistent with inferences about its emplacement during a cold period (Flaminio Auct.), the $^{40}Ar/^{39}Ar$ age of 546 ±3 ka for this pyroclastic-flow deposit supports the close correspondence with glacial MIS 14.2 lowstand (Figure 3b). The other volcanic deposit ("lower granular tuff") that Bonadonna associated with this cold period is the Tufo del Palatino (TP) which has an age of 533 ±2 ka, exactly matching the glacial termination VIa at the onset of MIS 13 (Figure 3b; Marra et al., 2017a). In perfect agreement with the sedimentary model for the aggradational successions, the TP is emplaced above the basal gravel layer of the Valle Giulia Formation (Figure 3a), and is covered by the early fining-upward succession deposited during sea-level rise of MIS 13.3 (Figure 3b). However, this sub-stage is shortly followed by a new sea-level fall culminating in the lowstand of MIS 13.2, causing a regressive phase during which the pyroclastic flow deposit of Tufo Giallo di Prima Porta (TGPP) is emplaced at 516 ±1 ka (Figure 3b).

The reconstruction of the sequence of sedimentary processes occurring during this time span is illustrated in Figure 3d, showing the initial accumulation of gravel within the paleo-incision of the Tiber river since the glacial termination at 535 ka (I), covered by the TP at 533 ka (II), and followed by aggradation of fine sediments until 524 ka (III), corresponding to the interstadial of MIS 13.3 (see also Figure 3d').

The occurrence of a temporary regressive phase 524 through 516 ka (IV) causes the partial incision of the early aggradational succession of the Valle Giulia Formation, and is highlighted by the unconformable contact of the TGPP above the TP, as seen in Via Flaminia where a 50 cm thick layer of gravel is intercalated between the two volcanic deposits, or directly above the older substrate, as seen in Cava Rinaldi (Figure 3d'). This regressive phase culminates in the lowstand of MIS 13.2 ca. 513 ka, shortly after the emplacement of TGPP, and is followed by a new sea-level rise caused by glacial termination VIb at the onset of MIS 13.1, during which the Grottarossa Pyroclastic Sequence emplaced at 510±4 ka (V). The upper part of the Valle Giulia Formation is emplaced during this second aggradational phase (VI), as evidenced by ages of 498 ±2 ka and 496 ±9 ka yielded by the Fall A deposits (Figure 3b) intercalated with the sedimentary succession in Cava Rinaldi (Figure 3d').

The combined chronostratigraphic and geomorphologic features of the sedimentary record of the Valle Giulia Formation exposed along the Tiber River Valley, summarized in the composite section of Figure 3d', represent an extraordinarily detailed proxy for the sea-level oscillations during the time span encompassing the glacial of MIS 14.2 through the interglacial of MIS 13.1. This sedimentary record, cropping out in northern Rome along the Via Flaminia, was already recognized as the Pariolian transgressive series in the chronostratigraphic scheme by Ambrosetti et al. (1972), which followed the Flaminian and preceded the Nomentanan erosional phases (Table 1). Also in agreement with Bonadonna's observation, the TRSN emplaced 452 ±2 ka during the climax of the marked glacial lowstand of MIS 12.2 (Figure 3b), and rests above deeply incised valleys within the deposits of the Valle Giulia Formation, as at km 8.2 of Via Flaminia (Figure 3a). Moreover, as Bonadonna correctly noted, the pyroclastic flow deposit is eroded after its deposition, consistent with the continued sea-level fall which occurred from 450 to 435 ka (Figure 3b), and the deposition of the lacustrine succession in Riano postdates the Nomentano cold period. Indeed, in Riano, like in all the Tiber River basin, sediment aggradation occurs in response to the sea-level rise of MIS 11.1, during glacial termination V, and is represented by the deposits of the San Paolo Formation (Figure 3b). In particular, the glacial termination is bracketed by ages of 436 ±6 ka yielded by a pyroclastic layer intercalated in the basal gravel layer in Pantano di Grano, and of 422 ±5 ka yielded by a fallout layer occurring immediately above it in Malagrotta (Figure 3c). The upper, fine-grained portion of the San Paolo Formation was deposited during the MIS 11 highstand, as evidenced by ages of 412 ±2 and 406 ±5 ka yielded by the tephra layers occurring at higher elevation within the sedimentary succession in Santa Cecilia and Riano, respectively (Figure 3a, b, c).

The San Paolo Formation was introduced only in 1995 by Marra & Rosa, and the proposed correlation with MIS 11 has been demonstrated by $^{40}Ar/^{39}Ar$ dating of the volcanic layers intercalated within the sedimentary succession cropping out at Pantano di Grano, Malagrotta and Santa Cecilia in the area of Ponte Galeria (Karner & Marra, 1998; Figure 2c). In contrast, only one transgressive phase dated at 280 ka, named Rianian after the abovementioned locality, was previously recognized, which was successively named Aurelia Formation and correlated with MIS 9 (Conato et al., 1980) (Table 1). However, recent dating at 406 ±5 ka of the fallout deposit occurring in the upper portion of the lacustrine succession in Riano provided evidence for reappraising its previous chronological and stratigraphic attribution to the MIS 9 and pre-dating it to the MIS 11, as well as for the three cervid skeletons found at this locality and consequently classified with the species name *Cervus rianensis*, which for decades have been considered typical of the MIS 9 Faunal Unit of Torre in Pietra (Marra et al., 2018).

Previous lack of identification of the occurrence of two full glacial cycles plus a minor sea-level oscillation in the time span 430-270 ka (see Table 1) was at the base of the widespread attribution to the Aurelia Formation and, successively, to MIS 9 of most of the geologic sections cropping out along the Via Aurelia (hence the Formation name) hosting the faunal assemblages of the Torre in Pietra Faunal Unit of the Aurelian Mammal Age (Gliozzi et al., 1997). Incidentally, the only section for which $^{40}Ar/^{39}Ar$ geochronologic constrains demonstrated a time of deposition compatible with MIS 9 is that exposed in Torre in Pietra (Villa et al., 2016), whereas all the other sedimentary successions previously attributed to the Aurelia Formation along the homonymous consular road have been re-assessed and placed within MIS 13 and MIS 11 (Valle Giulia and San Paolo Formations) (Marra et al., 2018), resulting in a deep revision of the biochronological context of the Aurelian Mammal Age (Petronio et al., 2018).

Unfortunately, application of the not properly accurate Uranium fission-track dating method resulted in a partial dismissal of the correlation between climate oscillations and the observed erosional/depositional phases. It was precisely the incorrect age of 0.225 ma yielded by a volcanic layer occurring at the top of the *tuffaceous-diatomitic* succession in Riano (Ambrosetti et al., 1969) (very likely the same fallout layer dated in Marra et al., 2018 at 406 ±5 ka), that induced these authors to conclude that "the local names provided by Blanc (1958) to the cold periods of the *Campagna Romana* should be considered completely unrelated with climatic oscillations, but linked with erosional phases mostly related with local tectonics". An unfortunate conclusion for an extraordinary series of field observations and insightful inferences!

6. A NEW CHRONOSTRATIGRAPHIC SCHEME

Widespread application of the worldwide attested $^{40}Ar/^{39}Ar$ dating method has substantially changed the chronology of the transgressive series recognized in this region, demonstrating a close match with even the minor glacio-eustatic sea-level oscillations in the marine isotope timescale for the equivalent aggradational successions. Besides giving back the deserved credit to Blanc's intuition, the new chronostratigraphic picture highlights the correctness of Bonadonna's accurate and insightful field observation, as shown in Table 1, and its invaluable contribution to successive studies. A fundamental link in this step forward was the work "New Data on the Pleistocene of Rome" by Conato et al. (1980), in which the basic framework of the local sedimentary successions which eventually became the aggradational successions was provided, along with the first tentative correlation with the stages of the oxygen isotope curve.

Based on the methodological approach described in Luberti et al. (2017), the stratigraphic scheme in Table 1 is an informal succession of UBSUs, defined based on the following criteria:

i) sedimentary units are deposited by an aggradational mechanism during glacial terminations in a time span encompassing the end of the glacial maximum through the subsequent interglacial stage;
ii) $^{40}Ar/^{39}Ar$ age constraints yielded by intercalated volcanic deposits provide correlation with the isotope chronology of Lisiecki & Raymo (2005) and stage numbering by Basinot et al. (1994);
iii) sedimentary units emplaced during the main glacial terminations are given the rank of Formation, while those emplaced during minor sea-level fluctuations linked with isotope sub-stages are given the rank of succession.
iv) stratigraphic nomenclature accounts for the originally introduced Formation names by the Authors, whenever stratigraphic position does not conflict with the successively achieved geochronologic constraints.

The sedimentary features of these aggradational successions encompass fluvial to lacustrine and lagoon to coastal facies, as described in Conato et al. (1980) and references therein. A detailed facies analysis of the deposits cropping out in the coastal area of Rome is provided in several papers (e.g. Milli et al., 2008, and references therein) describing a suite of fourth-order depositional sequences, whereas correlation of the deposits defined based on the sequence stratigraphic approach with the glacio-eustatically controlled aggradational successions of the Paleotiber River can be found in Marra et al. (2014b). Based on the revised definition of the stratigraphic sequence by Zecchin & Catuneanu (2013), all the recognized aggradational successions represent the innermost part of high-frequency sequences linked to glacio-eustasy.

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