bounding surface may occur. The second order sets are up to 2 m thick and represent the stacking of 3D dunes one over the other, forming compound sets and compound dunes with slightly sinuous crests.

Stop T.6.2.2
Acquafredda Mines (42°12’14.08’’N; 14°03’49.24’’E)

The areal distribution and the characteristics of bitumen seeps within the *Lepidocyclina* Calcarenite 2 can be estimated at this stop (Fig. 18).
The stop starts very close to the point where the Caramanico 1 well has been drilled in the 1976, reaching a total depth of 5540 m (Fig. 7, 17). The main target of this perforation was the supposed source rock represented by the Triassic Evaporites (Cazzini et al., 2015). This formation has been encountered from ~2850 m down to the total depth of the well, however, the Triassic Evaporites do not show evidences of activity as a source rock.
In the past, the Acquafredda area was one of the main sources for bitumen extraction, as it is possible to appreciate by looking at the abandoned mines (tunnels and trenches) that are widespread on this area. The shallow extraction activity deeply modified the topography, as shown by the several debris of the ancient extraction activity visible by walking toward the Colle dell’Astoro, (Fig. 18A). Such debris were heated in the furnaces to obtain asphalts ready to be sold. The intense activity is the main proof of the large amount of bitumen that was and still is permeating the Bolognano Fm in this area.
Two main NW-SE trending faults border the Acquafredda mines whilst in the middle of the area no major faults have been ever reported, nor they are currently observable in the field. However, the absence of large faults

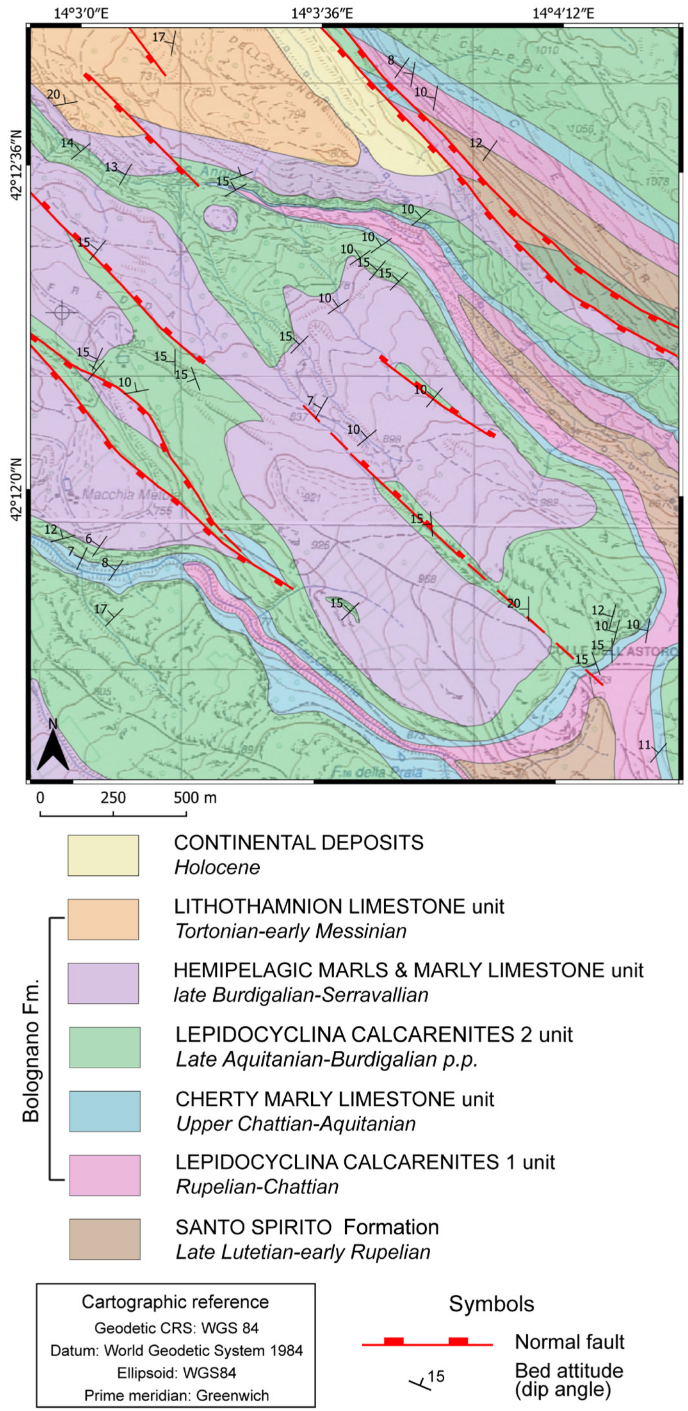

Fig. 17: Geological map of Acquafredda area.

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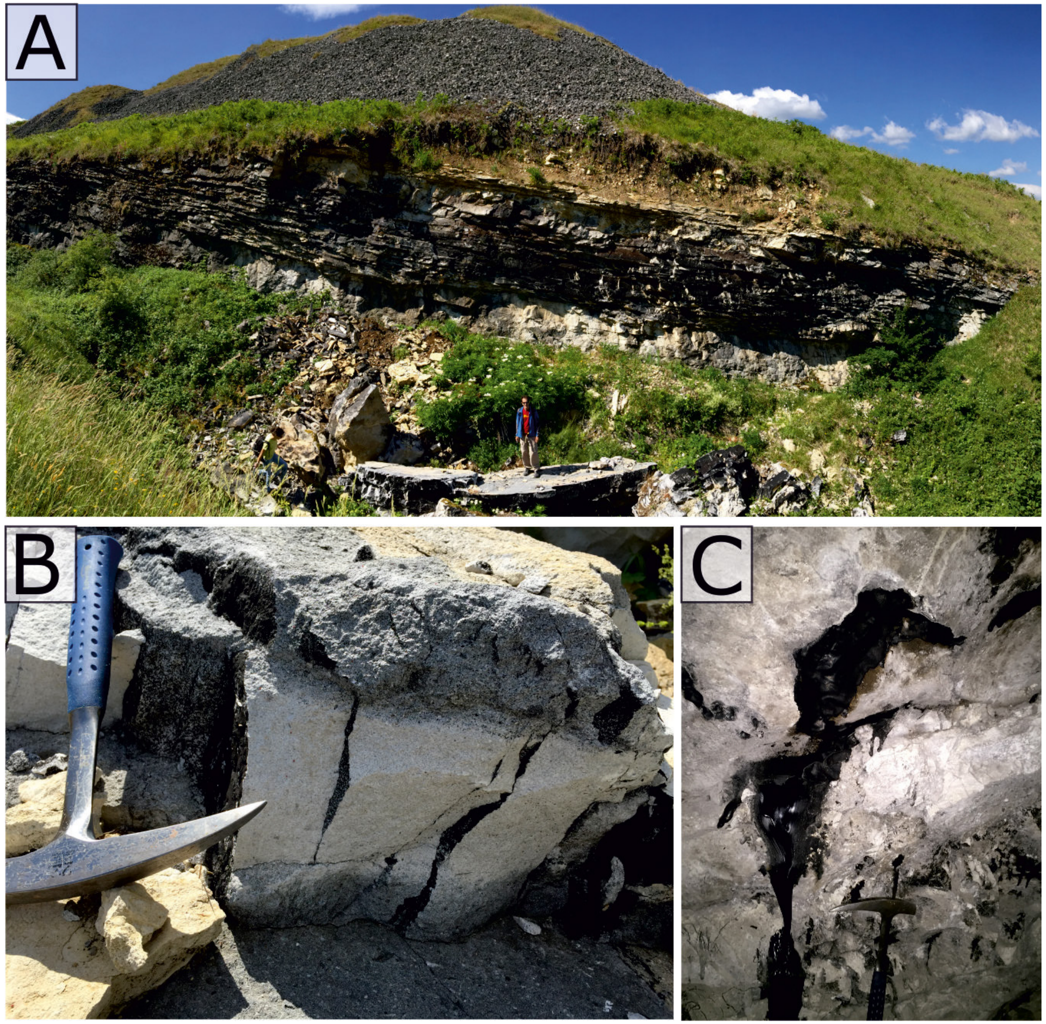

Fig. 18: Acquafredda mines, A) panoramic view of a trench within saturated *Lepidocyclina* Calcarenite 2. Note on top the debris resulted from the extraction activity. B) Detail of the saturated *Lepidocyclina* Calcarenite 2. Hydrocarbon saturation is evident close to the stratabound and within fractures planes. C) Bitumen that naturally flows out from a fracture in a mine tunnel.

nearby allows analyzing the fracture distribution in a homogeneous dataset not influenced by the presence of damaged zones. In a recent work (Trippetta et al., 2020), scanlines have been analyzed in order to investigate the role of fracture in the hydrocarbon circulation. Results show that fractures for both HHC-bearing and clean outcrops are mainly of the same type (joints-type with aperture not more than 2mm with few stylolites and very few small faults, Fig. 18A, B) and are characterized by the same orientation (NW-SE and NNE-SSW) in agreement with literature data on the Bolognano Fm (Di Cuia et al., 2009) and on older formations (Lavenu et al., 2014). The main difference between the two types of outcrops (clean and hydrocarbon-bearig) is that the absolute number of measured fractures is four times lower in hydrocarbon-bearing outcrops with respect to clean outcrops. It is also worth noting that the Colle dell'Astoro outcrop, located uphill along the Acquafredda path, shows higher fracture density (Trippetta et al., 2020) and it is free of hydrocarbon (Scrocca et al., 2013). This boundary has been proposed as the old oil-water contact (OWC) of this reservoir by Scrocca et al. (2013), while the difference in fracture density has been interpreted as a consequence of the different mechanical behaviour of hydrocarbon-saturated and clean rocks. Moreover, matrix saturation seems to be parallel to the bedding and thus not influenced by the orientation of fractures (Fig. 18B). On the other hand, fractures surely act as a drainage surface due to the increased permeability parallel to the fracture plane as frequently observed in the field (Fig. 18C). Trippetta et al. (2020) interpret this as an evidence of the fact that, when the last stage of fracturing occurred in this area, hydrocarbons were already in place. In this view, hydrocarbons flowed toward the newly formed fractures from an already saturated matrix, and the presence of hydrocarbons limited the formation of fractures with respect to clean rocks.

Stop T6.2.3
Valle Romana Quarry (42°14’23.73’’N; 14°03’26.00’’E)

The ancient Valle Romana bitumen quarry, exploited since Roman times, is located in the area of Lettomanoppello village (Fig. 1, 19). Impressive bitumen occurrences (“seepage”) characterize the outcropping biocalcarenites of the *Lepidocyclina* calcarenite 2 unit along a major fracture zone (Fig. 20A, C). This quarry offers a noteworthy outcrop where it is possible to observe the architecture of the Oligo-Miocene reservoir.
The quarry exposes the *Lepidocyclina* Calcarenite 2 unit and the overlying hemipelagic marls unit. In particular, on the SW wall of quarry, it is well evident the interdigitation of distal ramp lithofacies of the *Lepidocyclina* calcarenite ramp represented by the horizontally bedded marly packstone to wackestone and the sigmoidal cross-bedded grainstone (Fig. 21A, B). The main constituents of the marly packstone to wackestone are planktonic foraminifera, small benthic foraminifera, bryozoans, bivalves, and subordinately echinoids and serpulids. Glauconitic grains infilling planktonic foraminifera chambers are common. The beds are homogenous because of the *Thalassinoides*’ bioturbation traces. Thickness ranges between 10 to 30 cm. The beds are separated by 1.5 cm thick interval rich in clayey marls. The cross-bedded grainstone consists of a skeletal debris made of bryozoans and echinoids. Larger benthic foraminifera are still present. These cross-beds are inclined between 10 and 22°; the dip is generally toward WNW. The first order set are 20–60 cm thick. The sets are characterized by bedding-parallel lamination (bedding-plane discordant). The cosets (second order) are up to 5 m thick and are bounded by flat surfaces. The horizontal bedding style and the absence of cross-bedding in the marly packstone and wackestone lithofacies are indicative of deposition in low hydrodynamic conditions, the increasing of bioturbation, coupled with abundance of planktonic components, are typical of deposition in the distal outer ramp. On the contrary, the cross-bedded grainstone was produced by the migration of large, compound dunes in the distal portion of the middle ramp. The Valle Romana Quarry outcrop allows to observe the interfingering between middle and outer ramp environments.

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The vertical alternation of these two lithofacies represents the intervals characterized by the migration of the dune on the distal sediment of the outer ramp, alternating with intervals during which is predominant decreasing and interruption of sediment transport and decay of dune fields (Brandano et al., 2012).

This quarry also represents an excellent place to observe the structure of two oblique normal faults (Fig. 19A). This exceptional exposure made this quarry one of the most studied sites for fluid flow analysis in fractured systems (e.g., Agosta et al., 2009, 2010; Zambrano et al., 2019; Volatili et al., 2019; Romano et al., 2020). Most of the fault planes recognized in the outcrops are mainly northwest–southeast-trending normal faults (Vezzani and Ghisetti, 1998; Agosta et al., 2009; Romano et al., 2020) where some minor left lateral movements

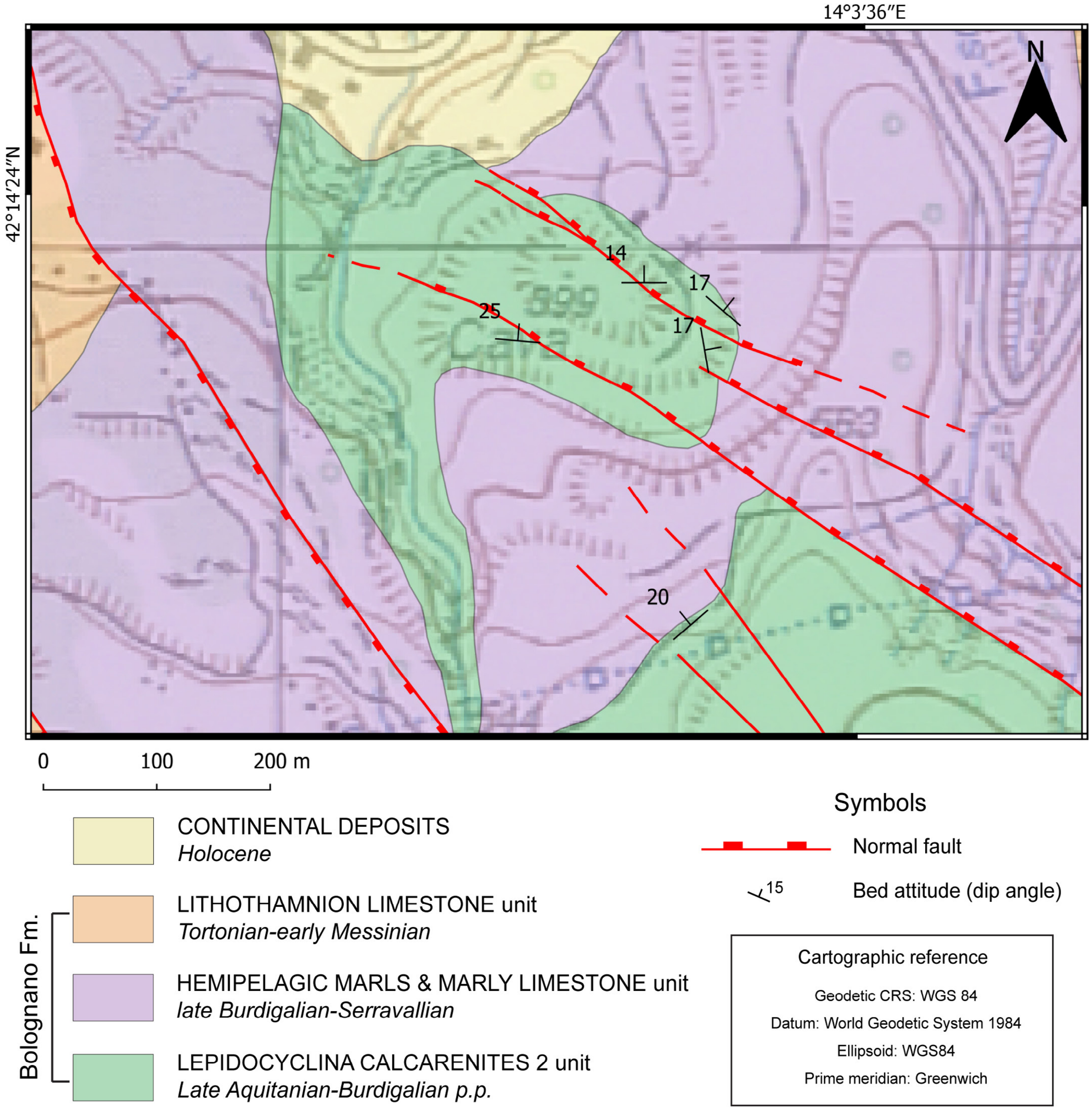

Fig. 19: Geological map of Valle Romana Quarry area.

are locally recognized (Agosta et al., 2010; Brandano et al., 2013). In particular, the SW fault dips 75° N and it is characterized by two main slip planes ~ N290° and ~N 300° (Agosta et al., 2010) with 40 m of throw. The NE fault is oriented ~N270° to ~ N315°, dipping 60° to 80° either N or S with about 10 m of throw. This fault pattern is considered the result of post-early Pliocene tectonic activity (Monaco et al., 1998; Ghisetti and Vezzani, 2002).

Agosta et al. (2009) deeply studied the fault rocks outcropping in this quarry. They documented predominant pressure solution-based deformation and shearing

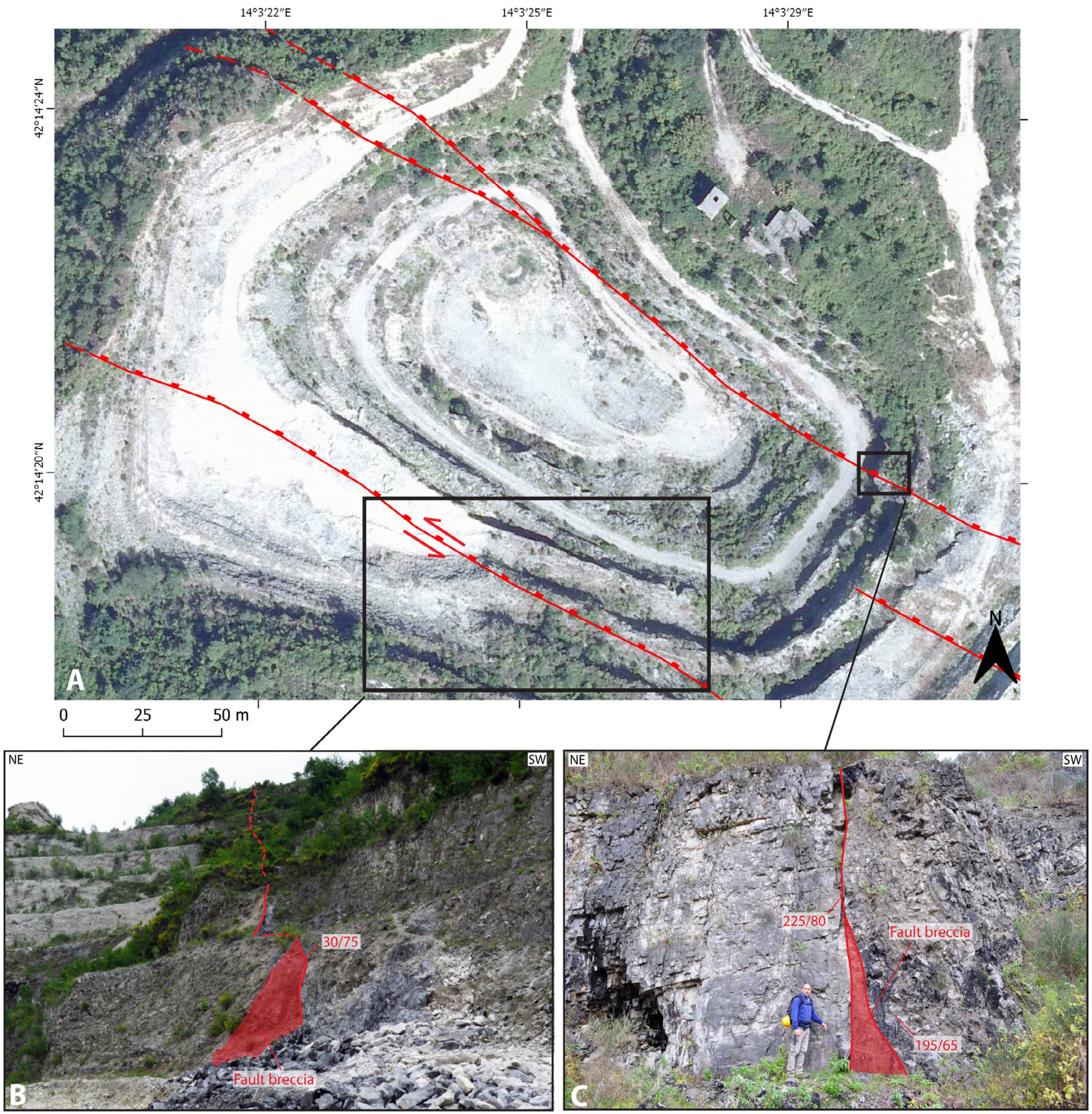

Fig. 20: A) Ortophoto of the Valle Romana Quarry. The line drawing shows the two large faults of the Roman Valley Quarry. B) SW fault in the Valle Romana Quarry. SW fault is oriented ca. N290°E, dipping about 70° and with a vertical throw of about 40 m. C) NE fault in the Valle Romana Quarry. NE fault is nearly sub-vertical, oriented NW-SE striking fault zone, with ca. 10 m of displacement.

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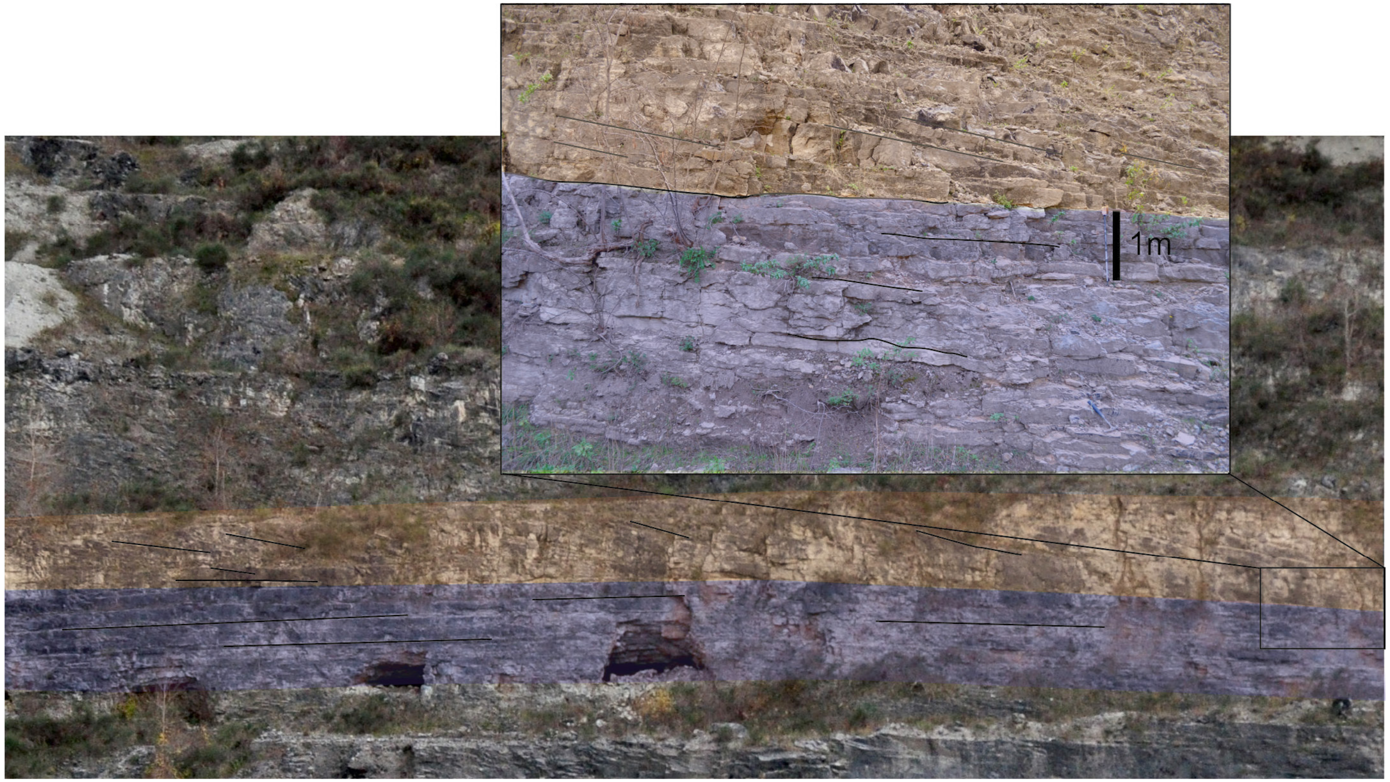

Fig. 21: The *Lepidocyclina* Calcarenite 2 is chacaraterized by two main lithofacies in the Valle Romana Quarry: the horizontal bedded marly packstone and wackestone (blue) and the cross-bedded grainstone (orange), produced by the migration of large, compound dunes on the distal portion of the middle ramp represented by the marly deposits.

of pre-existing discontinuities during the processes of fault initiation, and intensive jointing, dilation of the pre-existing structural discontinuities and cataclasis during the subsequent fault growth. The resulting fault architecture is comprised of an inner core of cataclastic rocks and brecciated carbonates surrounded by fractured and faulted carbonate damage zones (Fig. 19 and 20).
Field evidences clearly show that fault breccias and fault damage zones form conduits for fluid flow (Agosta et al., 2009, Brandano et al., 2013). It is worth noting that moving away from the fault zone, rock matrix still shows in some cases high hydrocarbon saturation being the matrix characterized by very high primary porosity (10-30%). This is in agreement to what observed in the Acquafredda mines, where relatively undeformed and unfractured rocks quite distant from fault zones where anyway saturated. Starting from a very dense dataset of shallow wells data, Lipparini et al. (2018) observed that even if fault-related fractured zones show high hydrocarbon saturation, this happens only when these faults cut across hydrocarbon-bearing primary-porosity reservoirs. They thus suggested a local impact of faults in draining hydrocarbons that should mostly postdate the main migration of hydrocarbons within the reservoirs, being the last deformation phase post-early Pliocene and possibly late Pliocene to early Pleistocene (Vezzani and Ghisetti, 1998; Ghisetti and Vezzani, 2002). Trippetta et

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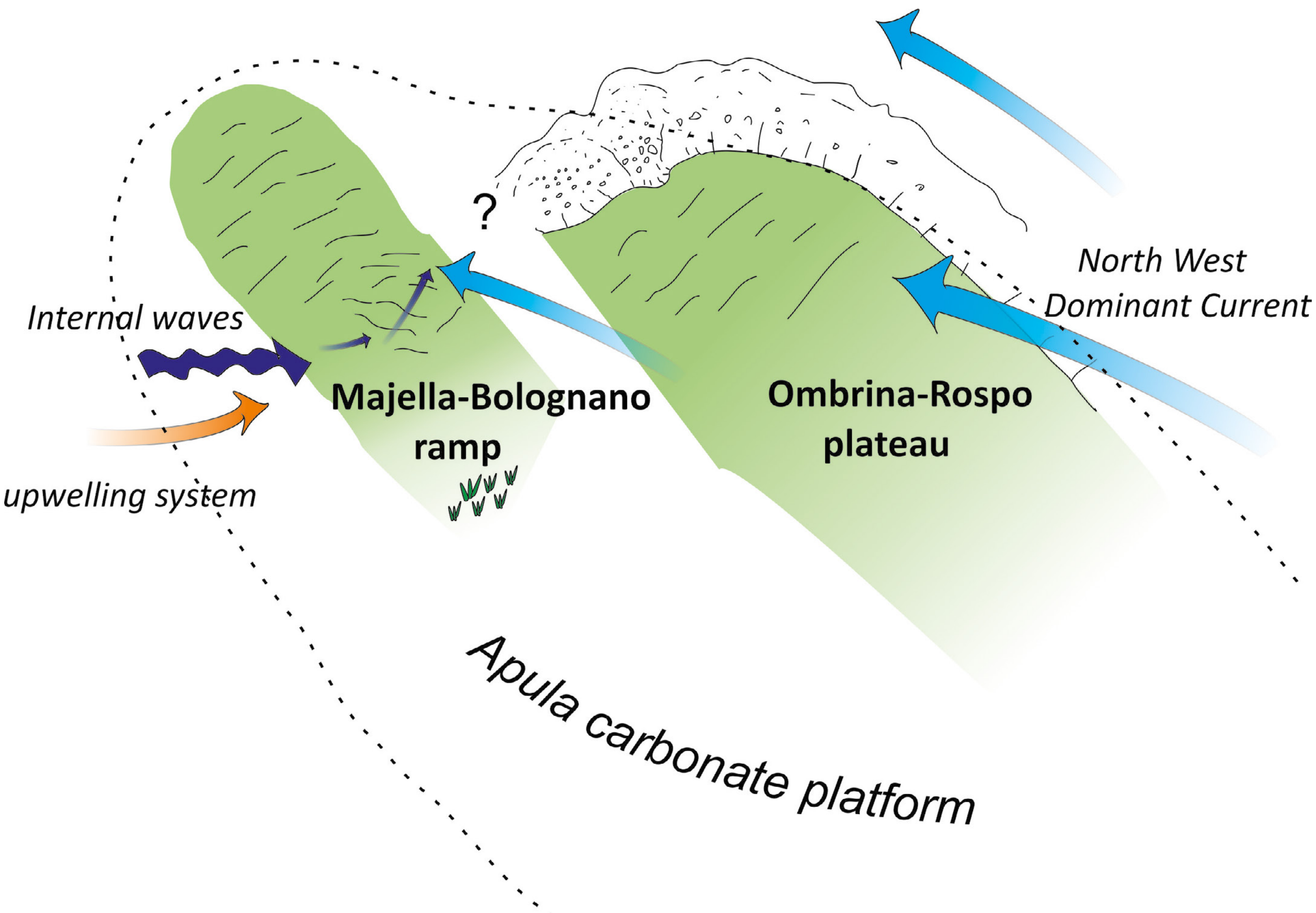

Fig. 22: Schematic paleogeopgraphy of northern Apulia carbonate platform and field dune development.

al. (2020) further suggested that this secondary oil migration was thus possibly driven from the high primary porosity and permeability of the Bolognano Fm. and due to its lateral continuity toward NW in agreement with Scrocca et al. (2013) that suggested the presence of the active source rocks in the northern areas where Triassic Evaporites are buried at larger depth.

Concluding remarks on dune field development

The 300-km wide proto-Adriatic sea was one of the largest seaways in the Mediterranean during the Burdigalian (Fig. 6) (Rögl, 1999; Dercourt et al., 2000; Popov et al., 2004). The eastern and the western boundaries of the proto-Adriatic sea were the Apulian carbonate ramp and by the Dinaride coast. The southern portion of the proto-Adriatic sea faced the wide eastern part of the Mediterranean.

The paleoceanographic reconstructions in the northern extension of the proto-Adriatic suggest the presence of a northward current and an amphidromic system (de la Vara and Meijer, 2016). The tidal wave rotated counterclockwise around the amphidromic point creating tidal currents traveling to the northwest.

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Interaction of the Mediterranean current and the tidal wave encroaching on the shallow-water Apulian ramp increased the flow speed. The accelerated current impinged bioclasts on the bottom producing the northwest migrating dunes (Fig. 2). However, northwest migrating dunes interbedded with 3-D northeast-directed dunes and phosphatic conglomerates rich of shark and fish teeth characterize the proximal portion of the middle ramp. Current research suggests these 3-D dunes may have been produced by internal waves propagated from the open southwestern portion of the proto-Adriatic sea and breaking on the northwestern sector of the Apulia ramp. Internal waves propagate along pycnoclines and are ubiquitous in the world oceans and lakes (Pomar et al., 2012, Pomar, 2020). Breaking internal waves or sloping surfaces causes a swash up-flow and a backwash return flow. The turbulence associated to the swash flow may produce erosion, and the backwash flow may produce transport of sediments downslope as bedload (Pomar et al., 2017; Pomar, 2020). However, the direction and the speed of the wash-up- and back-wash flows results from the wave energetics but also from the depositional dip angle of the ramp (Pomar et al., 2012, Pomar, 2020).

The internal waves are probably related to the upwelling system characterizing the Mediterranean and the Majella during the Burdigalian (Mutti and Bernoulli, 2003).

The presence of phosphatic conglomerates rich of shark and fish teeth interbedded in the cross-bedded succession testifies the occurrence of incipient hardgrounds related to upwelling currents propagating from the southwest to the northeast

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