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Sedimentary evolution and persistence of open forests between the south-eastern Alpine fringe and the Northern Dinarides during the Last Glacial Maximum

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ABSTRACT

We present a paleoenvironmental reconstruction for the mountain fringe between the South-Eastern Alps and the Northern Dinarides (NE-Italy/W-Slovenia) during the Last Glacial Maximum. We focused on a new sedimentary and paleoecological archive spanning the LGM acme, located in an aggrading, permanently flooded and ponded plain, dammed by an active fluvioglacial megafan. The ecosystem reconstruction, based on two high resolution pollen records, is supported by a rich plant macrofossil flora and constrained by a robust radiocarbon chronology between 26 and 22 cal ka BP. We show evidence for persistence of boreal trees and of different open boreal forest types throughout the LGM at the south-eastern mountain fringe of the Alps and the Northern Dinarides. Fire frequency is responsible for high, oscillating forest openness. The paleobotanical record is discussed in the light of the ecogeographic diversity of the region. A belt formed by Swiss stone pine, larch and dwarf mountain pine on limestone bedrock, and accompanied by Spruce in the floodplain, extended uphill, while proximal outwash plain supported Scots pine and dwarf mountain pine. These differences arise from groundwater regimes rather than from local climate variability. A steep moisture gradient from the semiarid pedoclimatic regime prevailing in the Adriatic alluvial plain to the forested mountain fringe is related to the orographic rainout triggered by southern air circulation. Mesophytic broad-leaved forest trees did not withstand the LGM temperature extremes in zonal ecosystems at the Alpine–Dinaric fringe; however, the fossil evidence suggests a number of microrefugia in karstic and thermal spring habitats of the northern Adriatic.

1. Contrasting environments in the Eastern Alps and the Adriatic Plain during the Last Glaciation — an introduction

The south-eastern fringe of the European Alps recorded abrupt environmental changes during the last glaciation. Piedmont lobes of the glaciers developed over the foreland (Fontana et al., 2014a; Monegato et al., 2007; Rossato et al., 2013) promoting aggradation and widening of outwash fans (Fontana et al., 2014b), which merged in the Adriatic Plain (Fig. 1). In fact, sea regression turned the northern Adriatic Sea into a terrestrial 150 km wide lowland, partly occupied by the Po River alluvial plain, collecting tributaries from the central Apennines, the south-eastern Alps and the Dinarides (Fig. 1; Maselli et al., 2014; Vai and Cantelli, 2004). The Po River delta was shifted 290 km southward at the culmination of the Last Glacial Maximum (LGM) sea level fall (Maselli et al., 2011, 2014; Trincardi and Correggiari, 2000). We acknowledge the definition of the LGM in terms of global ice volume, and with the span between 29 and 18 ka cal BP (Lambeck et al., 2014; Shakun and Carlson, 2010). A culmination between 27.5 and 23.3 ka, has been related to Greenland Stadial 3 (Hughes and Gibbard, 2014 and references therein).

Aeolian dust deposited along the edge of the Adriatic Plain (e.g., Cremaschi, 1990; Mikulčić Pavlaković et al., 2011; Zerboni et al., 2014), thus extensive deflation regions existed, such as semideserts, aggradating alluvial belts, and steppe. On the other hand the Alpine fringe experienced a wet, cold-temperate climate, related to orographic rainfall (Florineth and Schlüchter, 2000; Pini et al., 2010). During the LGM, this climate regime promoted both glaciation and forest trees survival on the southern flank of the Alps (Monegato et al., 2007; Šercelj, 1996; Schmidt et al., 2000). This area played a key role in the

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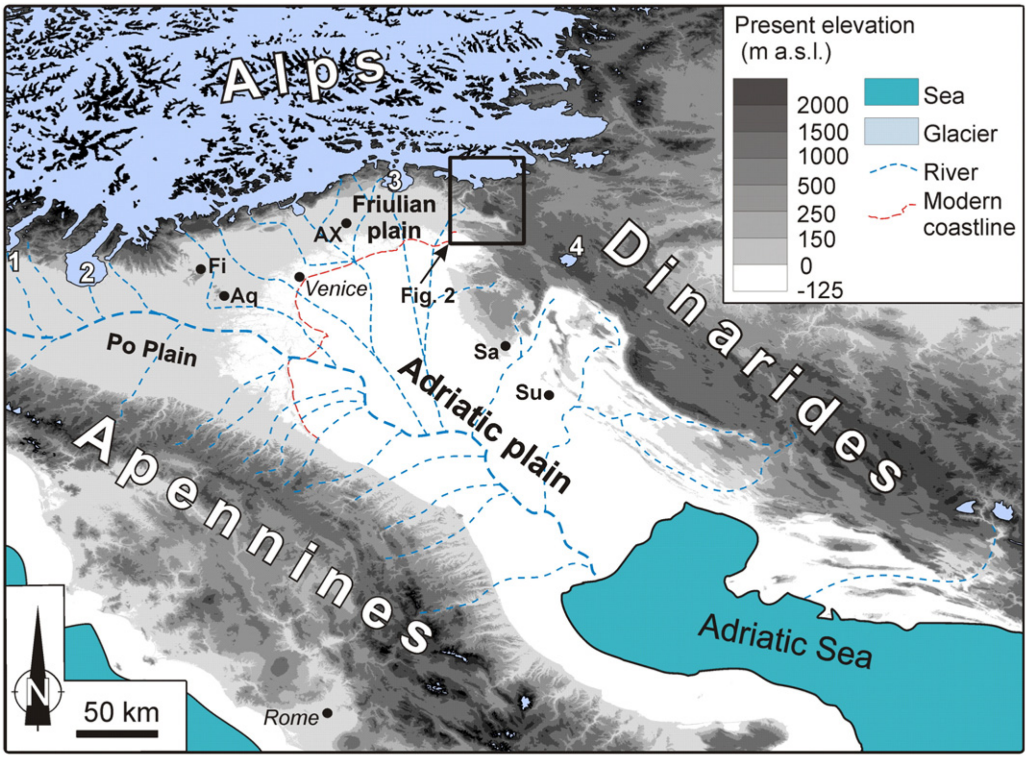

Fig. 1. Location of the study area (black frame) in the Adriatic area at the time of the LGM acme; the Adriatic Plain, coastline and the river pattern are drawn after Maselli et al. (2011, 2014) and the glacier extent after Ehlers and Gibbard (2004). 1: Oglio end-moraine system; 2: Garda end-moraine system; 3: Tagliamento end-moraine system; 4: Snežnik ice cap. Aq: Lake Arquà; AX: Azzano Decimo borehole; Fi: Lake Fimon; Sa: Šandalja II cave; Su: Susak Island.

tracks of animals (e.g., Canestrelli et al., 2012; Sala, 1990; Sommer et al., 2008), plant migration (Magri et al., 2006; Ravazzi, 2002), and human settlement (e.g., Peresani et al., 2014).

The atmospheric circulation during the LGM was characterized by a southward shift of Atlantic storm tracks, as evidenced by Alpine speleothem data (Luetscher et al., 2015), and may have enhanced rainfall on the southern flank of the Alps. The depressed Equilibrium Line Altitude (ELA) along the Southern Italian Alps–Dinarides is also related to a steep moisture gradient from lowlands to mountains facing the Mediterranean, thus promoting glaciation (Hughes et al., 2006; Kuhlemann et al., 2009). However, in the Dinarides, estimating local effects produced by orographic climate gradients is still a controversial issue (e.g., Adamson et al., 2014; Bognar and Faivre, 2006; Hughes et al., 2010; Marjanac and Marjanac, 2004; Milivojevic et al., 2008).

During the Late Glacial, the sea-level rise lead the Adriatic Sea to reach north to the Trieste Gulf, lapping on the Karst (Lambeck et al., 2004), surrounding the Istrian Peninsula and submerging former fluvial valleys, which had entrenched the Dalmatian coast during the glacial lowstand (Surić and Juračić, 2010). Hence, glacial/interglacial overturning had a dramatic impact over sedimentary environments and ecosystems in the Adriatic realm (Schmidt et al., 2000).

The present work presents the first precisely-dated record for the sedimentary evolution and the forest vegetation spanning most of the Last Glacial Maximum at the crosspoint between the south-eastern Alps (i.e., the Julian Alps), the karstic Northern Dinarides and the Adriatic Plain, presently drowned. A rich macrofossil flora spanning the LGM acme is presented, for the first time at the southern side of the Alps. Based on sedimentological and paleobotanical analysis of a new continuous record, and ^{14}C dating of macrofossil plant remnants, we examine relationships among regional geological framework, sedimentary environments, and forest history. Changes in the hydrological cycle triggered remarkable modifications on vegetation and landscape through 26 and 21 ka cal BP. These new finds in turn promoted a review of the fossil evidence in the northern Adriatic for identification of mid-latitude tree refugia.

2. Geological and geomorphological setting between the Julian Alps and the Northern Dinarides fringe

The study area is located near the Italian–Slovenian border, where the Julian Alps merge southward with the Northern Dinarides (Buser, 2009). The Julian Alps, characterized by carbonate massifs (Buser et al., 1986), reach 2864 m of elevation at Mt. Triglav (Fig. 2). The area is deeply carved by fluvial valleys, with elevation differences exceeding 2000 m in the core district. The Julian Prealps and the Karst are also dominated by carbonate rocks (Tentor et al., 1994), but portions of Paleogene flysch also occur, making impermeable patches within a generalized karstic landscape (Lewin and Woodward, 2009). The drainage network is divided in two main trunks, either flowing toward the Sava catchment and further to the Black Sea, or toward the Friulian Plain and the Adriatic Sea (Soča/Isonzo River). The Northern Dinarides can be split into distinct sectors (Fig. 2): 1) the “Classical” Karst, close to the sea, characterized by a flat carbonate plateau with average elevations below 1000 m a.s.l., and 2) the Trnovo Plateau to the North, whose elevation does not exceed 1500 m.

While Alpine rivers have wide catchments, with seasonal regime related both to snow-meltdown and abundant rainfall (Janža, 2013), those coming from the Northern Dinarides are strongly influenced by karst hydrology (Kovačič and Ravbar, 2010), thus showing underground reaches and enhanced sensitivity to heavy precipitations. The two hydrologic systems had different responses to climate changes during the Late Pleistocene.

The study area (Fig. 2) lays at the merging of the Soča River (Isonzo in Italian) and the Vipava River (Vipacco in Italian). The Soča River drains a 3,400 km^2 wide catchment, including the carbonate massifs of the Julian Alps (Fig. 2) and the Northern Dinarides, where the