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Messinian or Pleistocene valley incision within the Southern Alps

Sascha Winterberg^{*}, Vincenzo Picotti and Sean D. Willett

Abstract

Many of the valleys on the southern slope of the Alps are over-deepened, having bedrock valley floors well below sea level. This has typically been attributed to incision that occurred during the Messinian Salinity Crisis (MSC) when sea level dropped by hundreds of meters, leading to incision of many of the margins of the Mediterranean. We reassess this interpretation by documenting the correct elevation of the valley floor of the Adige river, one of the major valleys draining the Southern Alps, and by estimating the vertical motion of that valley floor since the end of Messinian incision. We re-evaluated the bedrock incision in the Adige valley using existing borehole data and seismic profiles. We estimate the vertical post-Messinian uplift using thermochronometric data that reveal the removed rock mass and then infer the expected isostatic uplift. These data are combined to reconstruct paleo-river gradients and to test viability of incision profiles. We find that the erosive surfaces in the drill holes restore to a paleo-elevation well below estimates of the Messinian Salinity Crisis (MSC) sea level. Restored valley gradients are often reversed compared to today's river gradients, as the uplift correction is higher upstream. A Messinian age of the erosional unconformities within the Alps can therefore be excluded based on the current best estimates of Messinian Mediterranean sea level and post-Messinian rock uplift. Pleistocene glacial erosion left a major signature on the geomorphology of the valleys, which is documented by glacially over-deepened valleys in the northern Alps. These valleys are not influenced by the Messinian sea-level drawdown. Therefore, it is suggested that the over-deepened valleys on the southern slope of the Alps are also glacial in origin.

Keywords: Alps, Messinian, Glaciation, Erosion, Adige river, Incision, Uplift

1 Introduction

Over-deepened valleys within the Alps are widely documented with bedrock surfaces far below today's valley bottom, and often below sea level (Preusser et al. 2010). Over-deepening describes a valley incision below a fluvial gradient. In the Alps, the mechanisms for such incision are interpreted differently north and south of the Alps. On the northern slope of the Alps a glacial origin was always the prevailing model for valley over-deepening (Hinderer 2001; Wildi 1984). On the southern slope of the Alps, the drawdown of the Mediterranean in the

Messinian led to incision of the Po Plain and the interpretation of fluvial over-deepening of valleys into the Alps, hence referred to as Messinian canyons (Bargossi et al. 2010; Bini et al. 1978; Cazzini et al. 2020; Finckh 1978). The observed data for both theories is similar and used to explain the Messinian river incision theory and the Pleistocene glacial over-deepening.

During the Late Messinian, the Mediterranean Sea was isolated from the Atlantic Ocean, and drawdown of the sea led to the Messinian Salinity Crisis (MSC) (Hsü et al. 1973). Several phases of sea level drop lasted tens to hundreds of thousands of years (Gargani and Rigollet 2007; Krijgsman et al. 1999; Roveri et al. 2014). The sea level drop caused incision of rivers draining into the Mediterranean Sea (e.g. Clauzon 1982; Ghielmi et al. 2013). After the final sea level rise, the incised canyons were filled with Pliocene marine sediments, sealing the

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unconformities that are preserved and dated to the end Messinian (Clauzon 1982; Ghielmi et al. 2013).

Pleistocene glaciation deeply eroded U-shaped Alpine valleys (Wildi 1984). Erosion was strongest at valley confluences and deepened the glacial valleys non-uniformly below their fluvial gradient (MacGregor et al. 2000). After glacial retreat, most basins were quickly refilled with sediments (e.g. Fuganti et al. 1998; Hinderer 2001); the perialpine lakes are the remaining evidence for the over-deepening. The basins have a sediment fill of up to a kilometre and a base at or even below sea level (Hinderer 2001; Wildi 1984).

Below the Po Plain and at the transition into the Alps, Pliocene marine to fluvial sediments are well described and dated due to intensive oil exploration (Ghielmi et al. 2013). Between Lake Maggiore and Lake Garda paleo-valleys below the Po Plain were incised during the Messinian Salinity Crisis (MSC) (Bini et al. 1978; Cazzini et al. 2020; Finckh 1978), and the seismic character suggests a filling with coarse material such as sandstones and conglomerates (Felber et al. 1991). More generally, in the Po Plain and the Adriatic Sea, the Pliocene sediments seal a late Messinian paleo-topography with a drainage network of incised canyons formed during the MSC (e.g. Amadori et al. 2018; Ghielmi et al. 2013). These well-studied canyon-filling Pliocene sediments in the Po Plain provide the base to interpret the undated over-deepened south-draining Alpine valleys as Messinian, although the sediment fill was never dated older than Late Glacial (e.g. Felber et al. 2000).

At the front of the Alps, between the Po Plain and the Alpine valleys, several outcrops of Pliocene sediments are described (Fig. 1), they are dated to late Zanclean and Piacenzian. From the west they are found at Malnate (Corselli and Gnaccolini 1985), Novazzano (Felber et al. 1991), and particularly around the outlet of the Brembo and Serio Rivers north of Bergamo (Brambilla and Lualdi 1986). At Cornuda and Bassano, the frontal ramp anticline of the Eastern Southern Alps exposes tilted Pliocene marine deposits on lower Messinian conglomerates, documenting incision and filling during and after MSC (Favero and Grandesso 1983; Monegato et al. 2009; Venzo et al. 1977). Finally, the highest elevation occurrence of dated Pliocene sediments on the foothills of the Southern Alps crops out at Monte San Bartolomeo above Saló west of Lake Garda (Fig. 1), where sediments are uplifted to an elevation of 500 m (Picotti et al. 1997; Scardia et al. 2015).

Pliocene sediments are filling V-shaped valleys at the transition from the Po Plain to the Alps (Amadori et al. 2018; Bini et al. 1978; Cazzini et al. 2020; Felber et al. 1991; Finckh 1978). The Messinian valley incision and Pliocene infilling in the Po Plain is widely acknowledged in the literature. The oldest filling of the Alpine valleys has been interpreted to be the same age. However, within the intramountain valleys of the Alps Pliocene sediments have never been found.

In this study, we test the hypothesis that the over-deepened valleys on the southern slope of the Alps are

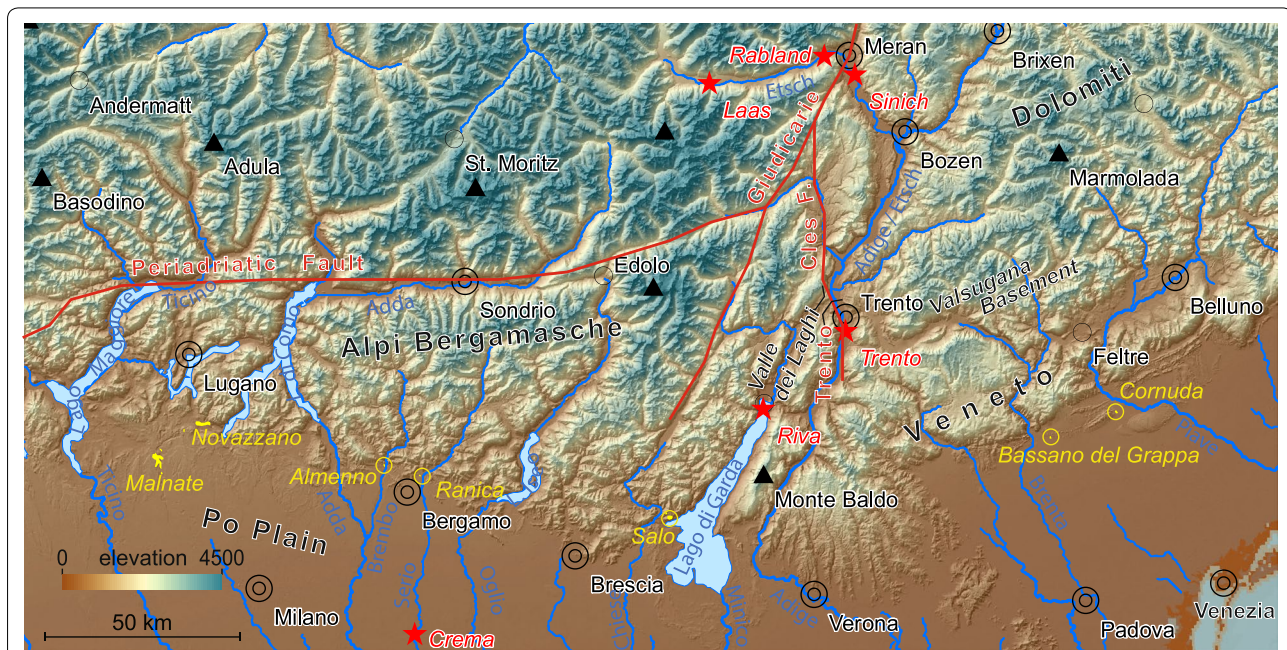


Fig. 1 Overview of the topography in the study area. Marine Pliocene sediments are marked in yellow. The cross sections of Fig. 2 are marked as red stars

preserved Messinian features. We focus on the Adige Valley where drill holes are described in Sinich (Bargossi et al. 2010 and references therein), and near Trento (Avanzini et al. 2010; Fuganti et al. 1998), and use interpretations of seismic profiles (Brardinoni et al. 2018; Felber et al. 2000; Savi et al. 2014). We then estimate post-Messinian vertical motion to test whether paleo-river gradients are consistent with the estimates of Messinian base level in the Po Plain and the Mediterranean.

2 Methods and relevant data

The study is based on seismic profiles, deep valley drillings, and a paleo-topographic model with uplift estimated from sediment volume data and exhumation estimated from thermochronometry. The data are put into context with the over-deepened valleys in the central Southern Alps. The seismic profiles and drill information provide an overview of the sedimentary fill and current rock surface elevations. We compare this with Messinian incision in the Po Plain and glacial incision on the northern flank of the Alps. Paleo-elevation and depth estimates are combined with erosion and exhumation data of the last 6 Myr, whereby we obtain an estimate for the total rock uplift of the valley floor during this time span. Paleo-river gradients are estimated on the basis of a reconstructed Messinian paleo-geographic map, and known paleo-river profiles.

2.1 Observations from drill holes and seismic investigations

The best studied sedimentary fill in the Adige Valley is a 2.3 km deep drill hole in Sinich between Meran and Bozen drilled in 2001 (Bargossi et al. 2010 and references therein). The drill hole is located 140 km within the Alps and hit basement 430 m below sea level; the sedimentary infill above the discontinuity is 700 m thick. The sedimentary sequence could not be dated but a seismic profile is available (Fig. 2c). The sequence above the basement rock was interpreted as high-energy fluvial sediment with well-structured, partially cemented, coarse gravels. Above this, a 350 m thick, fine-grained sequence was interpreted as lacustrine deposition (Bargossi et al. 2010). An angular unconformity in the overlying sequence, covered by sand and gravel deposits, is evidence for fluvial deposits again. The interval underneath these fluvial or glacial deposits is conformable. The basal unconformity was interpreted to be Messinian in age because it is overlain by a sediment that is interpreted to be alluvial, due to its facies, the continuity of the lacustrine sediments, and correlations with other valleys (Bargossi et al. 2010).

A study site close to Trento offers good seismic interpretations and a drill well. The site is 70 km within the Alps at an elevation of 185 m a.s.l. There, a 423 m deep

well did not reach the bedrock. The seismic interpretation assigns the elevation of the unconformity to 435 m below sea level (Fig. 2d). The fluvial to lacustrine sediment in the well is predominantly fine grained. The lower sedimentary infill in the Trento area is interpreted to be pre Last Glacial Maximum (LGM) (Avanzini et al. 2010; Felber et al. 2000).

Further studies describe over-deepened valleys on the southern flank of the Alps in the Lake Maggiore and Lake Como area, in the Adda Valley and around Lake Garda (Bini et al. 1978; Cazzini et al. 2020; Felber et al. 1991; Finckh 1978). The depth of the basement-sediment contact at the northern tip of Lake Garda, 50 km within the Alps, is 1100 m below sea level and suggests a V-shaped valley setting. The basal unconformity in that region is variable with elevations of 1100 m south of Riva del Garda and only 400 m a few kilometres north below Riva del Garda (Castellarin et al. 2005). Between the towns of Sondrio and Tirano in the Valtellina, 100 km upstream in the Alps, the valley unconformity is 200 m below sea level (De Franco et al. 2009; Gosso et al. 2012). Higher in the Adige valley there are also deeply eroded valleys. In Laas there is a 220 m thick valley infill (Brardinoni et al. 2018), and in Rabland 335 m of valley infill are observed (Savi et al. 2014) (locations Fig. 1, sections Fig. 2). Unfortunately, no longitudinal seismic section along a Southern Alpine valley was available, so it is not possible to make a definitive correlation along the valley.

Sedimentation rates in the glacially excavated valleys are high immediately after glacial retreat and decrease in the Holocene (Brardinoni et al. 2018; Fuganti et al. 1998; Savi et al. 2014). Wood fragments could be dated in the Trento well, they enable the reconstruction of the sedimentation rates. Calculated rates are not steady, but increase shortly after deglaciation at about 12 ka BP (Fuganti et al. 1998). The deepest dated sediment is 139 m below the surface, at about sea level and has a calibrated age of $12,385 \pm 245$ BP (Fuganti et al. 1998). Therefore, the region is interpreted to have been filled by more than 100 m of sediment in the last 12 ky. Similarly, sedimentation rates measured in the large Alpine lakes are also high after glacier retreat (Hinderer 2001).

2.2 Pliocene sediments

Late Messinian incision-surfaces are widespread in the sedimentary sequence of the Po Plain (Busetti et al. 2010; Ghielmi et al. 2013). Rivers incised deep valleys or even canyons into the Oligocene to Miocene sediments (Bini et al. 1978; Busetti et al. 2010; Felber et al. 1991). After incision, the valleys were filled with uppermost Messinian to Pliocene marine sediments, which provides an excellent age constraint for the incision event. However,

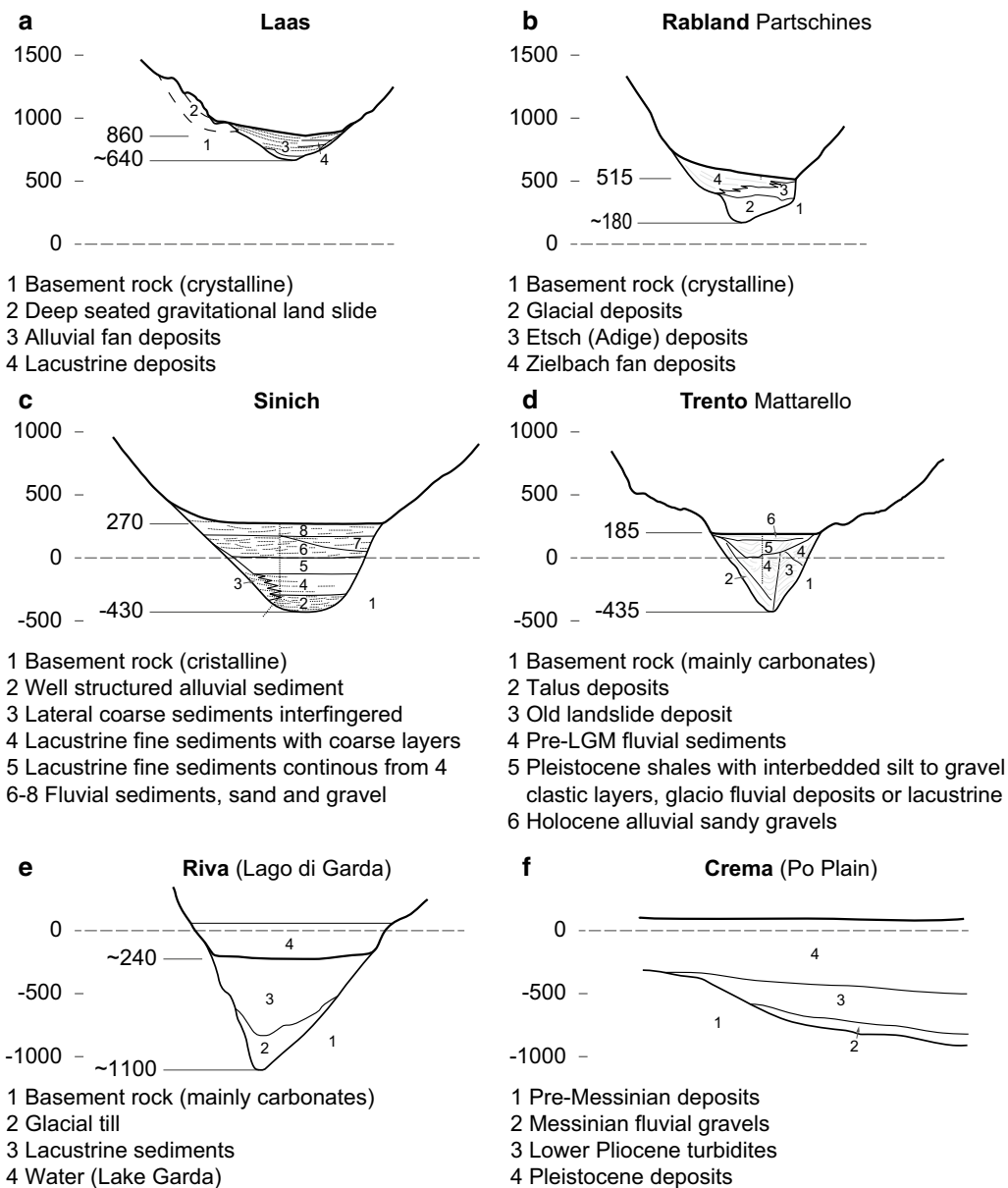


Fig. 2 Cross sections in the Adige Valley, the Lago di Garda and Po Plain showing the valley fill and the depth of the sediment bedrock unconformity (locations see Fig. 1). All profiles have a twofold vertical exaggeration, the drilling location is marked as a dotted line. **a** Laas section in the Vinschgau, seismic interpretation (modified after Brardinoni et al. 2018). **b** Rabland Partschines section 10 km upstream from Sinich. Seismic interpretation (modified after Savi et al. 2014). **c** Sinich section, the profile is based on seismic data and a drill hole and shows the sediment infill on the erosional unconformity that is interpreted Messinian in age (modified after Bargossi et al. 2010). Note that it is unknown if the valley bottom is U or V shaped, the original seismic line was not perpendicular to the valley. **d** Trento section was drilled to the pre LGM sediments but not into the basement rock (modified after Avanzini et al. 2010). **e** Riva (Lago di Garda), the section is in the not in today's Adige valley (Castellarin et al. 2005). **f** Crema (Po Plain), this section represents the incision, presumably Messinian, of the Serio or Adige river in the Po Plain (modified after Amadori et al. 2018). Note that the crema profile is in the subsiding Po Plain, the restored incision depth here is on the order of 750 m

documented preserved Pliocene valley infill is limited to the Po Plain and the foothills of the Alps.

Within the Alps, Pliocene sediments are very rare due to non-deposition and erosion. The uplift and exhumation in the Alps limits preservation of sediments of

Neogene age. Nevertheless, Pliocene marine sediments of late Zanclean to Piacenzian age outcrop close to the mountain front, for example in the mountain front in the Veneto region (Favero and Grandesso 1983; Venzo et al. 1977), where they are involved in compressional

structures (Fig. 1). In the western Southern Alps of the Lombardy, mostly undeformed Pliocene marine sediments outcrop at the mouth of intra-montane valleys, for example at Malnate near Varese (Cita and Corselli 1990; Corselli et al. 1985), near Novazzano (Bernoulli et al. 2018; Felber et al. 1991), and at Val Brembana and Val Seriana near Bergamo (Brambilla and Lualdi 1986; Siddi et al. 1988). In these localities, Pliocene marine deposits lap onto the flanks of the foothills at elevations between 250 and 325 m a.s.l. At the south-western tip of Garda Lake near Saló (Fig. 1), a decametre thick succession of uppermost Messinian, marine Pliocene, and continental Pliocene outcrops on top of ~100 m continental, possibly Messinian conglomerates (Picotti et al. 1997; Scardia et al. 2015). The sediments there are slightly deformed and uplifted to 500 m above sea level. This value is higher than the other western Pliocene outcrops; it can be related to a post-Pliocene activity of a local, tectonic structure (Scardia et al. 2015).

2.3 Erosion, exhumation, paleo relief and evolution of the Alpine elevation

The altimetry and the relief of the Alps is assumed to be relatively steady since the Miocene (Fig. 3) (Campani et al. 2012; Dielforder 2017; Kuhlemann 2007; Schlunegger and Kissling 2015). The mean paleo-elevation of the Alps was estimated with different methods: Isotope measurements, geophysical calculations and spacing between alluvial fans (Fig. 3). Isotopic measurements on micas at the Simplon normal fault revealed an elevation of $2350 \pm 700 - 500$ m at the onset of the Middle Miocene (Campani et al. 2012). Coulomb wedge calculation suggest that late Oligocene to early Miocene Alpine thrusts supported a mean maximum elevation of about 2000 m (Dielforder 2017). Spacing of Oligo-Miocene alluvial fans into the foreland basins combined with the

slope versus upstream catchment area relation result in a paleo-altimetry estimate of about 2000 m (Schlunegger and Kissling 2015). All elevation estimates are based on independent approaches, nevertheless they are strikingly similar. Even though all methods have large uncertainties, the Alps presumably had a quite steady elevation since the Miocene (Kuhlemann 2007).

Assuming the elevation is in steady state (Fig. 3), and rock uplift and erosion rates are equal, the exhumation rates or erosional flux rates can be interpreted as rock uplift rates. Even if this steady-state assumption is not true, isostatic uplift in response to erosional unloading is typically compensating more than 80% of the surface rock removal rate (e.g. Champagnac et al. 2009), so the assumption of steady state will not be more than 20% too high. A Pleistocene increase of sediment export out of the Alps points to deepened valleys and higher topographic gradients while maintaining the average elevation. However, the main assumption here is that the thermochronometry-based exhumation reflects the regional rock removal rate, not local possibly different rates.

Exhumation rates of the Alps are modelled for different periods by Fox et al. (2016) (Fig. 4a). Thermochronometric data were statistically inverted to quantify exhumation rates across the Alps since 32 Ma. However, only few data are available for the Southern Alps, and the data are mainly located in the Dolomites (Monegato et al., 2010; Zattin et al., 2006) or spread along the Periadriatic Fault, the major tectonic structure in the Alps. The approach of Fox et al. (2016) does not resolve specific discrete tectonic structures, but does provide a constrained average erosion rate. We limit the data to the best resolved areas as shown in Fig. 4a. The resulting exhumation rates in the Southern Alps are relatively low with maximum values of up to 500 m/My.

Erosion estimates of the Central and Eastern Alps are also calculated on the basis of sediment volume budgets around the Alps (Fig. 4b). The erosion rates reveal a general trend to lower values towards the Eastern Alps, with values ranging from 1000 to 60 m/My since the Pliocene (Kuhlemann 2007). In the upper Adige catchment, the erosion estimates vary from 200 to 400 m/My. These sediment-budget based rates show an increase in the Pleistocene (Kuhlemann 2007). However, the rates derived from this approach are lower than the thermochronometric erosion rate estimates. The differences could be caused by comparing large-scale catchment erosion with local exhumation rates, re-cycling of material, and uncertainties with the dissolved load (Kuhlemann 2007). Therefore, we assume that the estimated erosion rate from sediment budgets represents a minimum estimate.

Additionally, glaciation may have increased relief raising peaks and lowering valleys, while the average

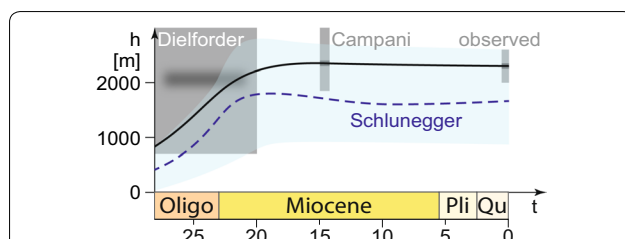


Fig. 3 Estimates of the Alpine elevation since Oligocene. Black line refers to the basis used for this study, with the Alps having a more or less steady elevation since Miocene. Mean hypsometric elevations from Campani et al. (2012), mean maximum elevation for Dielforder (2017) and paleo-altimetry estimate of Schlunegger and Kissling (2015). All estimates have large uncertainties but indicate steady mean elevation since the Miocene

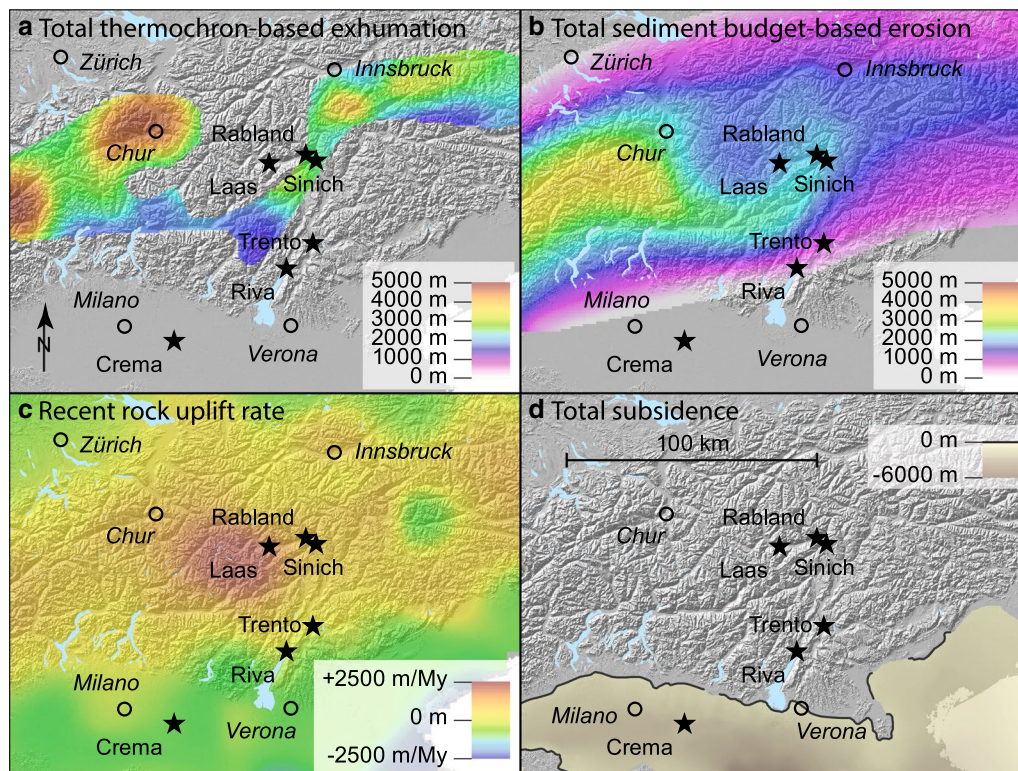


Fig. 4 Estimates of accumulated uplift from Late Messinian until present. **a** Thermochron-based model of Fox et al. (2016), note that the data quality is strongly variable, we only show the best resolved areas. **b** Sediment budget based model of Kuhlemann (2007). **a** and **b** use the same colour code for comparison. The thermochron based exhumation is larger than the estimations based on sediment budgets. **c** Present day rock uplift rates (Sternai et al. 2019). **d** Post-Messinian subsidence in the Po Plain inferred by interpretation of seismic reflection data shown in brown (Bigi et al. 1992), the black line indicates zero vertical motion since Messinian. The stars mark the locations of the cross sections in Fig. 2

elevation remained relatively stable (Champagnac et al. 2007). If erosion rates increased during the Pleistocene associated with more relief, the surface might go down on average, but rock uplift rate would still increase (Champagnac et al. 2007; Haeuselmann et al. 2007; Kuhlemann 2007).

An additional erosion rate estimate comes from cosmogenic ^{10}Be -based denudation rates, although these are representative for only the last few hundred to thousand years. In the Adige catchment these indicate erosion rates of 170 to 1400 m/My for the present (Norton et al. 2011; Wittmann et al. 2016), consistent with the rates from thermochronometry.

2.4 Faulting activity in the Adige valley

The tectonic activity since Messinian could have affected local uplift rates. There is some normal fault activity and minor tilting described in the Garda Lake area (Castellarin et al. 2005; Picotti et al. 1997; Scardia et al. 2015). Normal faults are mapped along the Garda Lake and the Adige Valley up to Bozen. However, although their prominent geomorphic expression, these structures did

not cause a major vertical displacement after Messinian (Avanzini et al. 2010), and in the Riva des Garda area they have a maximum displacement of 100 m (Castellarin et al. 2005). The Trento-Cles fault crosses the Adige valley at Trento and has only minor vertical offset, variable on both limbs due to the prevailing strike-slip motion (Avanzini et al. 2010).

In addition to these north–south striking faults, the east–west striking Periadriatic Fault possibly had strike-slip activity associated to Alpine extrusion tectonics to the east (Ratschbacher et al. 1991). This fault system includes the Giudicare Fault in the Adige region, which crosses the Adige in Meran. There are indications for post-Messinian activity of this fault system in the E–W trending Fella-Sava Fault located east of the study area (Bartel et al. 2014). As the Adige valley crosses these fault systems, it is important to note that no relevant vertical fault activity disrupted the valley (Bargossi et al. 2010).

2.5 MSC sea level and river erosion

In the late Messinian the Mediterranean sea-level was dramatically lowered by several hundreds of meters

(Table 1), in a desiccation event referred to as Messinian Salinity Crisis (MSC) (Gargani and Rigollet 2007; Hsü et al. 1973; Roveri and Bassetti 2001; Roveri et al. 2014). At this time the Mediterranean Sea was separated into different basins with different water levels (Gargani and Rigollet 2007; Krijgsman et al. 1999). In the western Mediterranean Basin, Messinian sea level estimates range down to -2000 m (Clauzon 1982), whereas in the eastern Mediterranean Basin the maximum drawdown estimates vary strongly (Madof et al. 2019; Roveri et al. 2014). The reconstructed sea level at the Rhône delta is 1600 m below today's sea level (Clauzon 1982). This value was discussed by Loget et al. (2006), considering the local isostatic adjustments. However, the sea level of the northern Adriatic Sea, including today's Po Plain, was independent. The drawdown was estimated to be 900 m lower than the mean global sea level (Amadori et al. 2018; Ghielmi et al. 2013).

Rivers draining into the Mediterranean experienced a strong incision pulse during sea level lowstand (Clauzon 1982; Roveri et al. 2014). Deep incised valleys are known from the Nile, Rhône, Tagliamento, Adda, Adige and more (De Franco et al. 2009; Felber et al. 2000; Finckh 1978; Krijgsman et al. 1999; Monegato et al. 2010; Monegato and Vezzoli 2011; Roveri et al. 2014). The transient incision pulse affected the upstream river profile. River profiles were unlikely to have reached steady state because the base level was fluctuating and drawdown was short lived. As a result, the river profiles have a convex shape, as demonstrated in the Messinian Rhône profile (Clauzon 1982; Gargani 2004). The convex profile of the Messinian Rhône gains 1000 – 1400 m of elevation in the lower reaches of the river (Clauzon 1982; Gargani 2004). Strong incision indicates generally high gradients in the profiles of the Messinian rivers.

2.6 Over-deepened valleys on the northern flank of the Alps

The main rivers north of the Alpine divide also have over-deepened valleys. The inner Alpine longitudinal profiles of the Inn, Rhine, Rhône and smaller rivers exhibit basins that are evidence for erosion depths below a river incision profile (Wildi 1984). The bedrock at the transition

into the Molasse Basin, where the Inn leaves the Alps, is as low as 500 m below sea level (Hinderer 2001). Except for the Rhône, which drains to the Mediterranean, there was no significant base level drop in the northern Alpine foreland that could have caused fluvial incision. Furthermore, the longitudinal valley profiles show a basin and swell trough morphology. Therefore, a glacial incision and over-deepening mechanism is widely accepted on the northern flank of the Alps (Hinderer 2001; Reitner et al. 2010; Wildi 1984).

This sediment filling on the northern slope of the Alps is also partially interpreted to be older than last glacial, perhaps even Pliocene (Hinderer 2001). Similar to the southern flank of the Alps, no outcrop of Pliocene sediments is dated or described on the northern flank of the Alps. However, most northern Alpine valleys are thought to have no Pliocene sediments because over-deepening processes are interpreted to be mainly Middle to Late Pleistocene (Preusser et al. 2011 and references therein).

3 Results and models

3.1 Paleo-geographic reconstruction and paleo-river basin properties

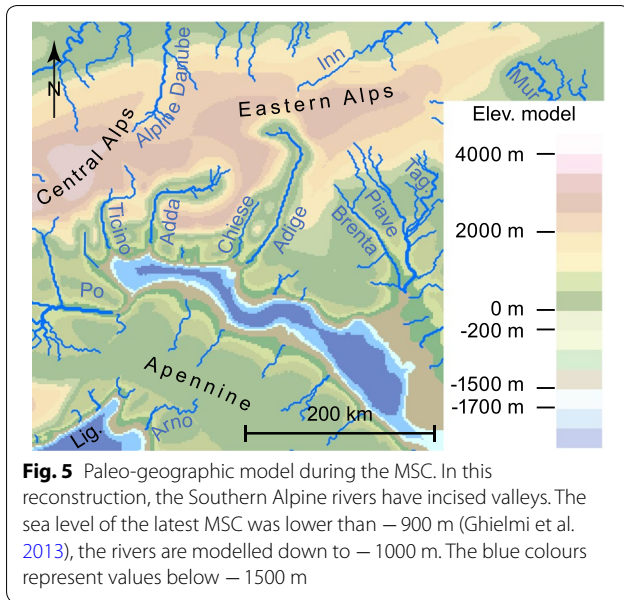
We modelled a Messinian paleo-geography using the data of the incised MSC river locations and other paleo-geographic reconstructions (Fig. 5). The underlying elevation model is based on Kuhlemann (2007) and further elaborated for this study. The position and catchment geometry of the rivers draining the southern flank of the Alps did not change much since Tortonian (Fantoni and Franciosi 2010).

An important question regarding the paleo-geography is whether the Adige was flowing through the Lake Garda valley or if it already had its separate, more easterly valley. In the late Miocene, coarse clastic sediments document that the paleo-Adige entered the fore-deep basin south of the lake Garda (Ghielmi et al. 2010). However, the location of this paleo-delta fits with both paleo-river courses.

A paleo-river course through the Lake Garda would require that the Adige paleo-river profile was higher than the bedrock pass between Trento and the Valle dei Laghi (Fig. 1), today at 600 m a.s.l. Such a high in the paleo-Adige profile would make it impossible to have Messinian

Table 1 Estimates of sea level drop during Messinian

| References | Sea level drawdown | Basin |
|-----------------------------|---------------------------------|------------------------|
| Ghielmi et al. (2013) | 800 m (700 – 900 m) | Po Plain |
| Amadori et al. (2018) | 800 – 900 m | Po Plain |
| Roveri et al. (2014) | 1500 m (West), 800 m (East) | Complete Mediterranean |
| Gargani and Rigollet (2007) | 500 – 1500 m | Complete Mediterranean |
| Clauzon (1982) | 1600 m | Western Mediterranean |



incision at 435 m below sea level in the Adige valley above Trento. A normal fault that offsets the rock 1000 m after Messinian would be required to offset the incision. However, the post-Messinian activity of the north–south striking Trento–Cles Fault system is unknown, a vertical offset of 1000 meters is not described but also cannot be excluded.

Another possible paleo-river course is the current course of the Adige. Pliocene conglomerates containing clasts of the Valsugana Basement, found at the present outlet of the Adige Valley (Scardia et al. 2015), document an old river valley from Trento following today's Adige Valley. However, a course from today's valley position at the Alpine front to the entry point in the fore-deep requires a canyon immediately in the Alpine foothills that connects to this entry point. Such a valley or canyon from the Adige to the Lake Garda is not documented.

A paleo-Adige river course through the Lake Garda and a river course similar to today are equally possible. To resolve this problem, we assume that the river course always followed today's valley and had a connection with a canyon to the Lake Garda and the fore-deep. However, the influence of the paleo-location of the valley on the models is small because the profile length is very similar. Therefore, the profile models are using the scenario where the paleo-Adige course follows today's valley.

3.2 Maximum possible Messinian river incision depth

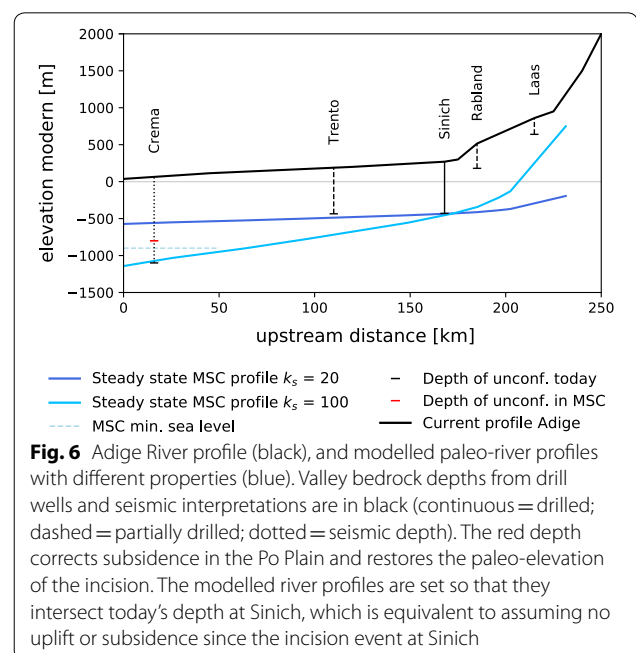
A detailed river profile analysis was performed based on the paleogeographic model. With the paleogeographic data we can model the river basin geometry and the

river network. The river network itself serves as a base to integrate catchment area. We calculate area-normalised channel length, χ with $A_0 = 1 \text{ m}^2$, $x_b = -1000$ m (Perron and Royden 2013), and the concavity set to $\frac{m}{n} = 0.45$ (Wobus et al. 2006).

$$\chi(x) = \int_{x_b}^x \frac{A_0}{A(x')^{\frac{m}{n}}} dx'$$

Based on a simple slope versus catchment area relationship, we calculate the elevations along the Adige river (Perron and Royden 2013; Wobus et al. 2006) (Fig. 6). This elevation profile is pinned at the observed unconformity in Sinich (Fig. 6). We use the integral form of the slope area relationship and include the steepness to calculate the profile elevation, $z(x) = k_s \chi$ (Kirby and Whipple 2012; Winterberg and Willett 2019). We model river steepness with an alluvial gradient, $k_{s,a} = 20$, and a bedrock gradient, $k_{s,b} = 100$. Note that it is very likely that the Adige had a convex MSC river profile, as seen for example at the MSC Rhône profile (Clauzon 1982). Such a profile would further increase the river gradient.

The reconstruction of a paleo-gradient of the Adige River can test the possible incision depth during the MSC. To evaluate the incision depth, modelled river profiles and the base level are compared. However, as sea level is debated the base level of the rivers is not a well-defined elevation. Therefore, the model pins all profiles to the unconformity elevation of the Sinich drill well, hereby fixing the profile to the observed incision and testing if profiles fit to a sea level (Fig. 6). Distance and



the elevation difference to the inferred Messinian base-level during the MSC can be estimated from the reconstruction of the paleo-geography.

The paleo-river gradient defines the elevation difference from base level to the point of interest. Today, the elevation loss from Sinich to the Po Plain is about 200 m. Similarly, the Messinian Adige had at least this gradient, which would correspond to a MSC sea level of -630 m. Furthermore, today's river profiles have a typical concave shape close to a steady state profile. Therefore, the situation during the MSC likely would have been different: The rivers had also convex zones in the profile because of short-lived sea-level drawdowns and therefore short incision phases. Consequently, the elevation gain must be larger than with a concave steady state profile.

To estimate the situation with a convex river profile, we compared the MSC Adige River with the geometry from the MSC Rhône River. Starting a gradient at the known depth in Sinnich, and using the Rhône without a correction for catchment area, provides an estimate of a MSC Adige River base level. The Rhône profile of Clauzon (1982) shows for the first 80 km a gradient of 9‰ followed by a slope of 1.8‰. Similarly, the distance from the late Messinian base-level to the Trento unconformity is more than 80 km and to Sinich 150 km. Using this rough estimate of the paleo-gradient would result in a base level of about 720 m lower than the Trento unconformity and about 850 m lower than Sinich. The respective sea level would be -1155 and -1280 m. These required sea levels are more than 250 m lower than previous estimates (Amadori et al. 2018; Ghielmi et al. 2013). Therefore, the incision depth in Sinich is not realistic using a convex paleo-river gradient. The estimates of the MSC base level (Ghielmi et al. 2013) and depth of the Trento unconformity are incompatible with a Messinian paleo-river gradient.

3.3 Estimations of the integrated amount of uplift since Messinian

Messinian surface elevation correction for uplift and subsidence is based on exhumation ages and sediment budget calculations. A Messinian surface elevation must be higher today, if it was affected by uplift in the meantime.

Thermochron based exhumation rates since Messinian are around 500 m/My in the upper Adige Valley (Fig. 4). The accumulated exhumation since the Messinian based on thermochron data is about 2650 m in Sinich. The total exhumation along the Adige River reveals similar values. The exhumation since the Messinian in the Valtellina is lower but still around 2000 m. The quality of the thermochron data is reliable

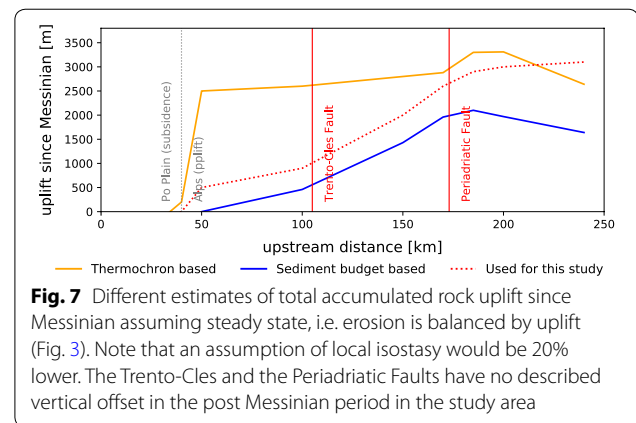


Fig. 7 Different estimates of total accumulated rock uplift since Messinian assuming steady state, i.e. erosion is balanced by uplift (Fig. 3). Note that an assumption of local isostasy would be 20% lower. The Trento-Cles and the Periadriatic Faults have no described vertical offset in the post Messinian period in the study area

in the area around Meran because the data integrates time since late Miocene. The exhumation rate towards the Po Plain is not constrained, due to the lack of data.

Uplift estimates based on sediment volumes are of similar magnitude. The erosion is generally lower than 500 m/My in the Adige Valley (Fig. 7) (Kuhlemann 2007). The erosion rates are increasing with time from 200 to 500 m/My (Kuhlemann 2007). This results in a total accumulated erosion since the Messinian of 1770 m in Sinich (Appendix 1) (Kuhlemann 2007). The accumulated erosion in Trento since the Messinian is around 1230 m (Kuhlemann 2007). The spatial pattern of total erosion shows a decrease of erosion towards the Po Plain, and an increase towards the Central Alps (Fig. 4). The estimated erosion is reaching zero towards the transition to the Po Plain and is assumed to better reflect the rates in the carbonate-dominated southern parts of the Southern Alps. The erosion rates are considered to represent a minimum estimate due to a possible underestimation of the dissolved load.

The reconstruction of the Messinian Salinity Crisis (MSC) river profile in Fig. 6 does not consider rock uplift since the Messinian. Therefore, an estimation of the total uplift of any rock particle since the Messinian is required to determine the modern elevation of a Messinian valley surface (Fig. 8). Having steady average elevation of the Alps, as suggested by different sets of geological data (Campani et al. 2012; Dielforder 2017; Schlunegger and Kissling 2015) (Fig. 3), implies that erosion was balanced by uplift, and estimates of exhumation can be used as direct measure of rock uplift (Fox et al. 2016; Kuhlemann 2007).

To estimate the elevation of a rock surface formed in the Messinian, the accumulated uplift since then has to be subtracted from today's elevation. With steady Alpine altimetry and the described exhumation rates, all Messinian erosional features would have been significantly

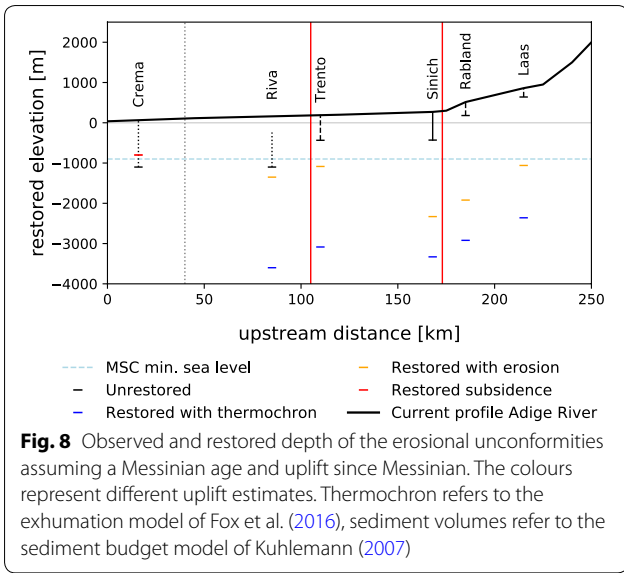


Fig. 8 Observed and restored depth of the erosional unconformities assuming a Messinian age and uplift since Messinian. The colours represent different uplift estimates. Thermochron refers to the exhumation model of Fox et al. (2016), sediment volumes refer to the sediment budget model of Kuhlemann (2007)

uplifted since. This implies that features formed in the uplifting Alps, formed at a far lower elevation (Figs. 8 and 9).

The sediment-bedrock-transition in the Sinich well is at 400 m below sea level. Uplift since the Messinian is between 1765 and 2650 m in Sinich. Including this accumulated amount of uplift, a Messinian altitude of the Sinich incision surface would be at 2165 m or even 3050 m below today’s sea level.

The well in Trento has a bedrock surface at 435 m below sea level. The accumulated uplift is between 1229 and 2650 m. A Messinian altitude of the incision surface at Trento would be at least 1664 m below today’s sea level.

4 Discussion of preserved MSC incision in the inner Alps

The interpretation of preserved Messinian Salinity Crisis (MSC) incision surfaces is based on observations all along the southern margin of the Alps, i.e. at the transition to the Po Plain and the Plain itself. In this latter area, marine Pliocene is onlapping the bedrock incised during the Messinian, spanning the Mesozoic to the Lower Messinian (Brambilla and Lualdi 1986; Corselli et al. 1985; Favero and Grandesso 1983; Venzo et al. 1977), and can be correlated to canyon fillings below the Po Plain. There, V-shaped incisions visible on seismic profiles suggest that fluvial incision reached the front of the Alps and is preserved there (Bini et al. 1978; Finckh 1978). Further upstream in the Alpine valleys, well-structured, but not dated sediments are found in a well 400 m below sea level. These sediments are covered with conformable lacustrine sediments with inter-fingering hillslope deposits (e.g. Sinich well in Fig. 2c). Therefore, the valley fill has been interpreted as a Pliocene analogue to the canyons in the Po Plain. This line of evidence is prevailing in recent interpretations about Southern Alpine valley over-deepening (Amadori et al. 2018; Avanzini et al. 2010; Bargossi et al. 2010; Cazzini et al. 2020).

Our results and models present evidence that is clearly conflicting with the assumption of preserved MSC river incisions in the core of the Alps. Our observations challenge the prevailing interpretations with multiple independent arguments:

First, river profiles that are set to the elevation of the incision depth in Sinich require a base level lower than current estimates of the MSC sea level (Fig. 6) (Ghielmi et al. 2013). Furthermore, such an equilibrated river

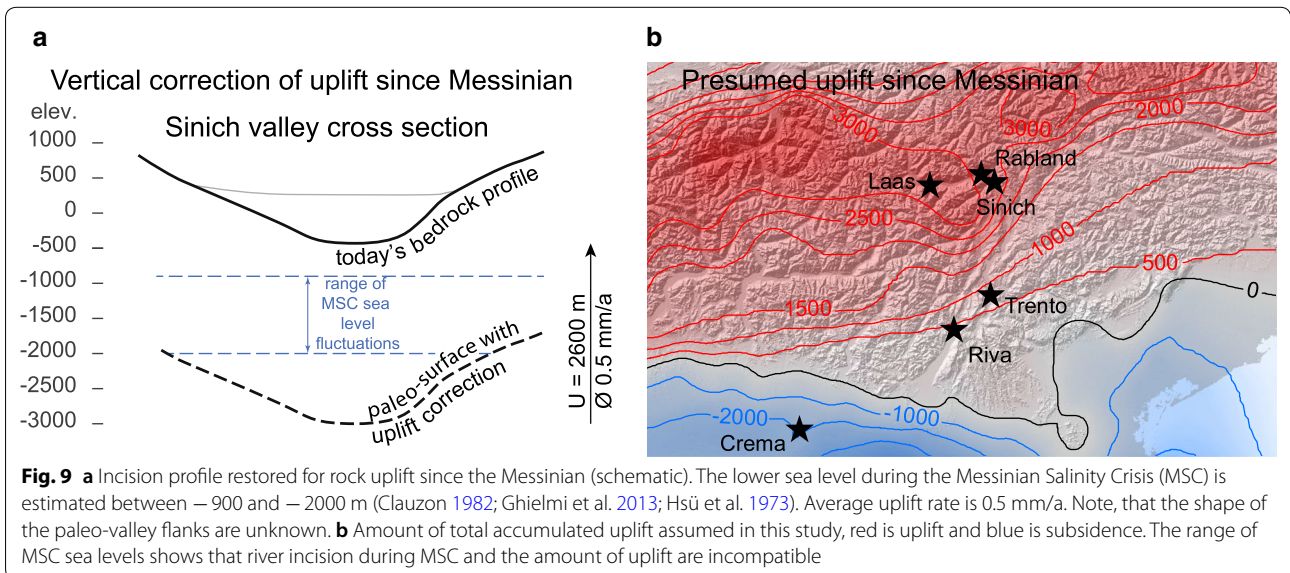


Fig. 9 a Incision profile restored for rock uplift since the Messinian (schematic). The lower sea level during the Messinian Salinity Crisis (MSC) is estimated between -900 and -2000 m (Clauzon 1982; Ghielmi et al. 2013; Hsü et al. 1973). Average uplift rate is 0.5 mm/a. Note, that the shape of the paleo-valley flanks are unknown. b Amount of total accumulated uplift assumed in this study, red is uplift and blue is subsidence. The range of MSC sea levels shows that river incision during MSC and the amount of uplift are incompatible

gradient would require a long lasting, low sea level. We know from the Rhône River that an equilibrium profile was not achieved (Clauzon 1982). With a realistic convex paleo-Adige gradient for the MSC, the sea level must be more than 1200 m below today's sea level. This is significantly below proposed MSC sea levels of Ghielmi et al. (2013) or Amadori et al. (2018).

Second, the observed elevation of the Trento unrestrained unconformity is almost at the same elevation as the unconformity in Sinich. To have river incision, a gradient towards the base level has to be present. The observed elevations do not follow a bedrock gradient between the two points. Therefore, a river gradient between the Sinich and Trento is unlikely.

Third, rock uplift since Messinian due to erosion must be considered. Elevations of incision surfaces have to be restored for uplift and subsidence since the time they formed. If the surfaces are considered Messinian in age, the uplift since the Messinian has to be subtracted from today's elevation, and to the current elevation added in the case of subsidence. Considering this correction, most profiles are restored at depths of more than 2000 m below sea level. This is much lower than any sea level estimate during the MSC (Amadori et al. 2018; Gargani and Rigollet 2007; Ghielmi et al. 2013). Hence, no Messinian fluvial incision would have been possible, because the rock surface would have been below sea level in the Messinian.

Fourth, the lacustrine sediments in the well of Sinich may have formed in a periglacial lake. A Late Pleistocene age of the undated sediments is very likely, and would explain why no datable material was found. Late Glacial radiocarbon dates between 12.5 and 14 ky cal BP are recorded in lacustrine deposits drilled in the subsurface of the Adige Valley near Trento, at depth of 139 to 217 m below the present valley bottom, which is between 61 and –15 m above sea level (Avanzini et al. 2010). Furthermore, the observation of the high-energy, well sorted sediments at 430 m depth in Sinich can be explained with subglacial, pressure-driven current deposits that sorted the clasts (Pfiffner 2010; Röthlisberger 1972). Such sediments exist also on the north-western flank of the Alps, for example in the Rhône valley where the incision is interpreted to be Pleistocene to Holocene (Buechi et al. 2017; Hinderer 2001). Comparable lacustrine sedimentary infill is shown in the Lienz Basin where its formation is clearly linked to glacial cycles (Burschil et al. 2019).

We conclude that the MSC river incision hypothesis implies a set of unrealistic or even impossible conditions. Having a Messinian incision surface in Sinich, and at the same time a MSC sea level estimate at minus 900 m, results in two unrealistic scenarios: With a steady state river profile, only 300 m of rock uplift are possible (Fig. 6), and with a steeper profile, uplift has to be

reduced to zero. However, the incision event was short-lived and could not reach a steady state profile, and uplift is shown to be much larger. This argument questions a preserved Messinian surface in Sinich and leads to the uplift argument that challenges all preserved Messinian surfaces in the inner Alps.

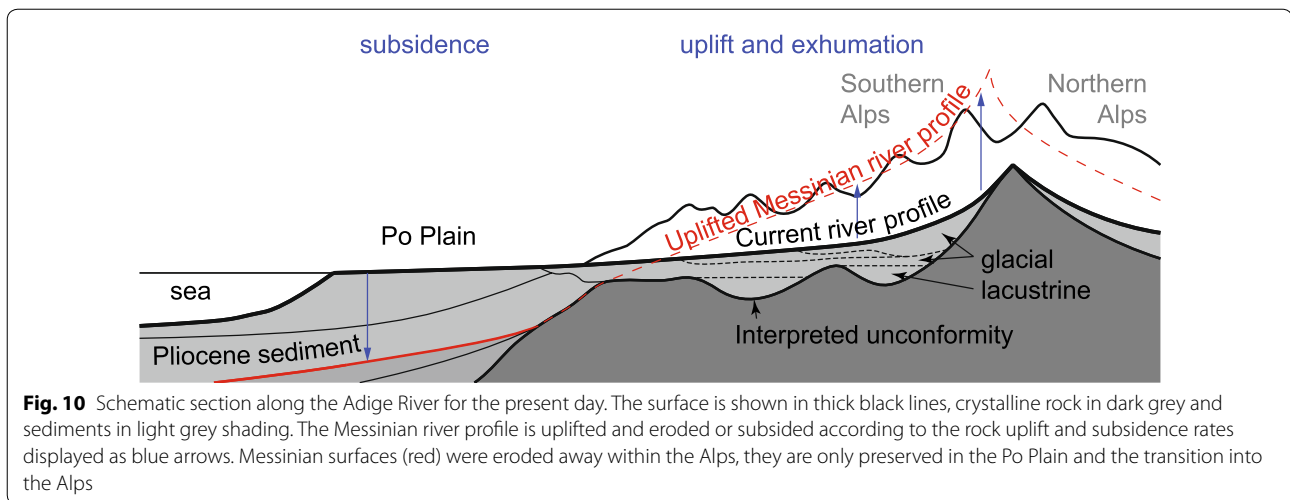
The major argument to rebut preserved Messinian incision relies on erosion and exhumation estimates (Fig. 4). The amount and quality of the data to constrain uplift in the vicinity of the boreholes is limited. Nevertheless, the used rates are of a reasonable magnitude to fulfil tectonic and structural geological models (e.g. Schmid et al. 2004) and generally agree with ^{10}Be denudation data (e.g. Wittmann et al. 2016). A minimal uplift must be assumed in any case due to erosion. The studies for uplift and erosion agree well, the magnitude of uplift is robust. Until today, Messinian unconformities are uplifted above the surface and therefore not preserved (Fig. 10).

As all valleys on the southern flank of the Alps have a similar evolution, a preservation of Messinian paleo-river profiles in the inner Alpine valleys is very unlikely and probably only possible at the transition zone in the foothills of the Alps between subsidence of the Po Plain and uplift of the Alps.

We propose a glacial genesis of the erosive surfaces on the southern slope of the Alps. We think that additional drillings and seismic investigations would come to a different description of the valley infill. We predict that a longitudinal seismic profile of the Adige Valley would reveal a basin and swell structure instead of a river gradient, due to stronger erosion and deepening at glacial confluences (MacGregor et al. 2000). A basin and swell bedrock erosional geometry has been recently documented for the Lago Maggiore by (Cazzini et al. 2020). The processes of formation of the Southern Alpine valleys can be directly compared to the basins already identified on longitudinal seismic profiles of the northern Alpine valleys (Hinderer 2001; Preusser et al. 2011).

5 Conclusions

Uplift since the Messinian in the Southern Alps was spatially variable but significant. Rock uplift has changed the elevation of every surface that formed in the Messinian. Therefore, the observed depths of the bedrock unconformities have to be corrected for the post-Messinian uplift if they are assumed to be Messinian in age. The post-MSC uplift due to erosion can be estimated from thermochronometry-based estimates of exhumation and sediment budgets. Assuming orogenic steady state so that rock uplift is equal to erosion, the surface elevation at Sinich has to form at least 1700 m deeper than it is today, the surface at Trento at least 1200 m deeper.



However, the lowest drawdown of the MSC estimated by Ghielmi et al. (2013) or Amadori et al. (2018) was at -900 m, higher than the restored Messinian elevations of the surfaces in Sinich and Trento.

The sea level during the MSC remained low for only a few short periods. A range of MSC river gradients shows that fluvial erosion could not even incise the unrestored depth of the observed unconformity in the Adige valley, if the profile was out of steady-state. Therefore, incision during the MSC is not possible, the erosional unconformity must have formed differently.

Glacial incision is generally considered to explain the over-deepened valleys in the Northern Alps. The valleys south of the Alpine divide probably have the same incision mechanisms. Therefore, a glacial origin of the Sinich, Trento and potentially most inner southern Alpine unconformities is proposed. The process of formation of the Southern Alpine valleys should be revisited.

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Authors' contributions

Sascha Winterberg conceived the paper, collected the data, did the modeling and most writing. Vincenzo Picotti helped framing the topics, providing regional expertise, and participated writing the manuscript. Sean Willett contributed ideas concerning isostatic equilibrium, and gave feedback to the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The paleo-geographic models are available on <http://www.paleotopography.com>.

Competing interests

The authors declare that they have no competing interests.

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