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Addendum to Diercks et al., 2021: A model for the formation of the Pradol (Pradolino) dry valley in W Slovenia and NE Italy

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Abstract

In our paper Diercks et al. (2021) we presented geomorphological data and field observations from W Slovenia and NE Italy to develop a model for the formation of the Pradolino (slov. Pradol) dry valley. After publication we were kindly pointed to existing studies on the area that we were unaware of. To fill that gap and to properly credit previous work, in this addendum we summarise the research history on the study area and briefly compare earlier views with our model.

Introduction

In our paper Diercks et al. (2021) we developed a model for the formation of the Pradolino (slov. *Pradol*) dry valley using geomorphological analyses and field observations. After publication, we were made aware of previous studies that investigated the geomorphological evolution of the area. These papers were mainly published in the 1980s and 1990s in Italian geoscience journals. In order to give proper credit to earlier work, we summarise these studies here. For the sake of completeness, we also include older studies from the Italian and German literature that date back to the 19th and early 20th centuries. In the following we will use Italian names for locations that are on Italian territory today, and Slovenian names for locations that are on Slovenian territory. For clarity, such toponyms in the respective other language are put in parentheses and in italics. For the same reason, original quotes from earlier papers are also put in italics.

Research history

The Pradolino dry valley is located in NE Italy and interpreted as a former course of the Nadiža river (ital. *Natisone*), when the valleys now occupied by the river were blocked by glaciers. Its entrance lies about 200 m above the course of the Nadiža and it is deeply incised between Monte Mia and Monte Vogu. The Nadiža takes a highly curved course around Monte Mia (Fig. 1) at present. Notably, it does not enter the wide valley between Robič (ital. *Robis*) and Kobarid (ital. *Caporetto*), where it could join the Soča (ital. *Isonzo*) river, but it turns sharply south towards Stupizza (slov. *Šupca*). This conspicuous geomorphology has caught the attention of various scholars.

The general geology of the study area was studied in a modern sense since the 19th century, for example by Štúr (1858). He already described the low drainage divide between the present-day Nadiža and the Soča east of Robič. The divide is only a few meters higher than the floor of the wide and U-shaped valley and mainly consists of a landslide deposit that originates from the northern flanks of the Matajur mountain (Fig. 1.). Štúr, however, classified all moraines as of Tertiary age. This notation made it even into the map of Stache (1889), although Taramelli (1870) pointed out this erroneous age assignment.

The evolution of the fluvial system and the geomorphology in the area has, however, already

been a matter of debate much earlier. This debate rested on field observations and the interpretation of historical texts, especially on the change of geographical names. It would lead too far to summarize the discussion, which started as early as in the 16th century, and the interested reader is referred to the extensive work of Tellini (1898), who provided a broad overview. The debate about the Nadiža and Soča rivers, together with the birth of modern geology, can be seen as the driver of an intensification of research on the area. Especially the work of Kandler was used as a starting point for a long-lasting discussion.

Pietro Kandler, a historian from Trieste, argued that the Soča had flown from Kobarid towards the west in Roman times, occupying the Staro Selo (ital. *Starasella*) valley. It had then joined the Nadiža near Robič, from which it reached south towards Stupizza (Kandler, 1864, 1867). He claimed that the landslide near Robič occurred in 586 or 587 AD due to a flood event. With the valley being blocked, the Soča would have been dammed and finally occupied its present-day course towards Tolmin (ital. *Tolmino*) and Most na Soči (ital. *Santa Lucia d'Isonzo*). Kandler's theory faced harsh criticism based on archaeological and geological arguments.

Taramelli (1871) argued against Kandler's theories. He considered it impossible that the Soča once had flown to the west. Instead, he held the view that the western branch of the Soča glacier blocked the Staro Selo valley and forced the Nadiža to flow south, instead of continuing to the east and joining the Soča. He also already stated that the Nadiža might have occupied the Pradolino valley. In later publications, Taramelli described glacial deposits in the Nadiža valley and reaffirmed the view that the glacier advanced via the Staro Selo valley from Kobarid as a branch of the Soča glacier (Taramelli, 1875). Taramelli (1882) summarized the debate about a possible connection of the Nadiža/Natisone and the Soča/Isonzo system based on archaeological and historical arguments by Kandler and others (Kandler, 1864, 1867). Again, he strongly opposed Kandler's views and argued that the course of the Nadiža towards Stupizza was established following the abandonment of the moraine of Staro Selo, which blocked the connection between the Nadiža and the Soča. Taramelli was the first one to have established a more or less correct view on the Soča glacier according to Penck and Brückner (1909).

Von Czoernig (1873) was fond of Kandler's interpretation and suspected that the Soča once flowed from Kobarid to the west in the Staro Selo valley, where it joined with the Nadiža at Robič. He argued based on the wide valley floor, the almost flat morphology between Kobarid and Robič, and fluvial gravels. He detailed historical arguments based on ancient texts, going back even to Plinius and Strabo, from which he concluded that the Nadiža once must have had more erosive power. However, even with von Czoernig's assertive support, Kandler's ideas could not prevail for long.

In his dissertation, Gumprecht (1886) worked on the relation between the Soča and Nadiža rivers. He outrightly rejected Kandler's hypotheses and argued that the Nadiža once (after the Tertiary) followed the valley of Staro Selo to Kobarid, where it joined the Soča river. Only later, he argued, did the Nadiža turn south at Robič to occupy its present-day course. Gumprecht reported that the drainage divide near Staro Selo is made up of moraine material, and that the landslide masses only form the very top of the divide. He detailed on the distribution of glacial deposits in the area and on the slope of the Staro Selo valley, which he reported to be clearly inclined towards the east with a vertical drop of ca. 20 m along a 5 km stretch between Robič and the Soča bridge near Kobarid. He concluded that there were four stages of drainage development: First, after the Tertiary, the Nadiža used the Staro Selo valley to join the Soča. Second, during the pre-glacial period, backward erosion in the Pulfero-Stupizza valley caused the Nadiža to flow to the south, at least partly. Third, during the glacial period, the Soča glacier blocked the Staro Selo valley up to Sedlo and Logje; the Nadiža had to turn south at Robič and perhaps even used the Pradolino gorge. Fourth, in post-glacial times the Nadiža continued to use the course it has today. A small tributary to the Soča originating in the Staro Selo valley, the Idrija, got repeatedly dammed by material from the Šjak stream, causing temporary lakes and leaving lacustrine deposits in the Staro Selo valley.

Gumprecht's arguments against Kandler were partly confirmed by the archaeologist Gregorutti (1890) based on the interpretation of historical and archaeological data. However, Gregorutti claimed that there never was a communication between the Nadiža and the Soča systems at all – a claim that should never find wide support.

Marchesetti's (1890) work did not add any more observations to the distribution of glacial deposits other than Gumprecht's, although Marchesetti dealt in detail with the age of the Staro Selo

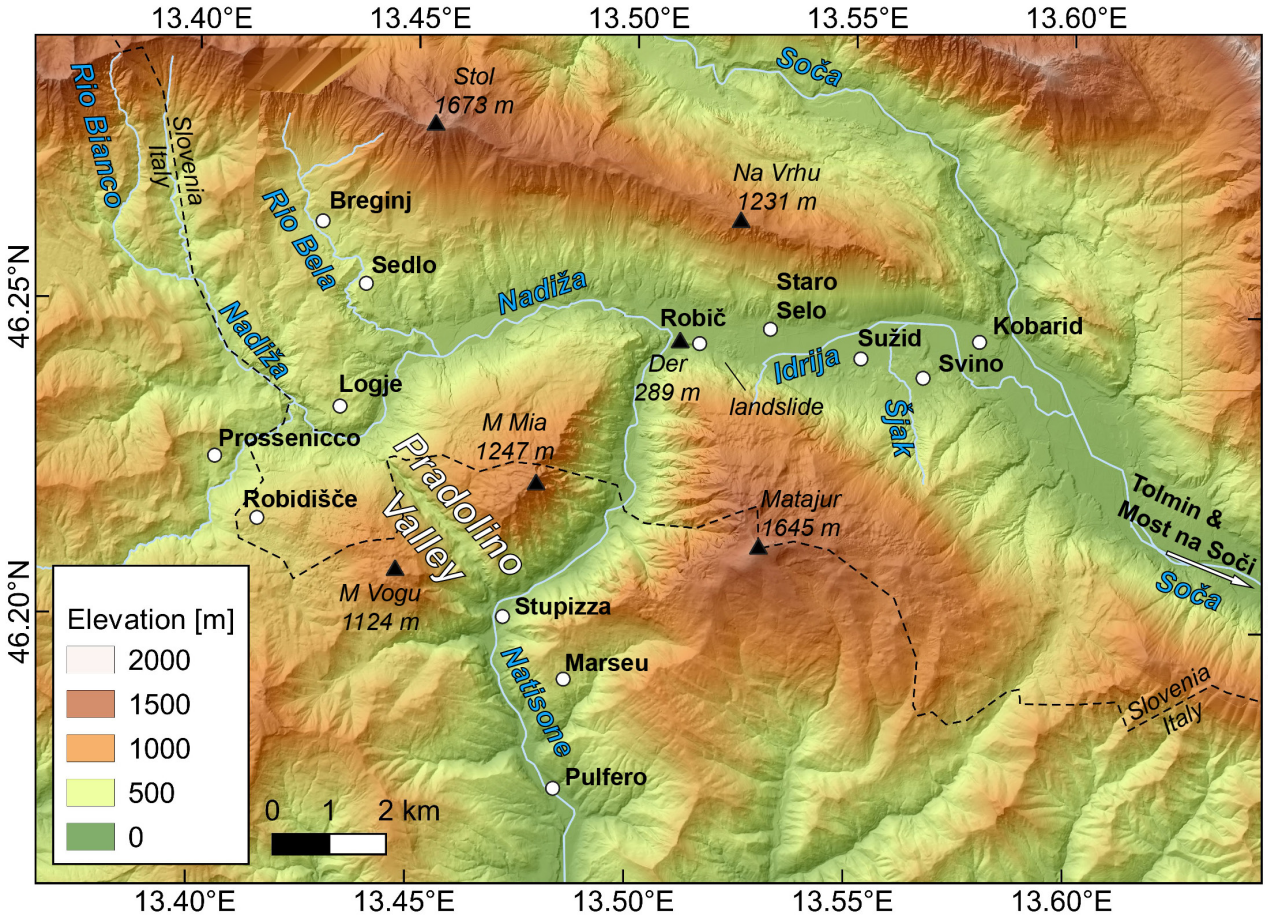

Fig. 1. Map of the study area in NE Italy and W Slovenia. Digital elevation data are from ARSO (2020) and Tarquini et al. (2007).

valley. For example, he assumed that the rockfall near Robič might have occurred in 586 AD based on local oral tradition and the limited amount of erosion that can be seen in the rockfall boulders. He argued that the Nadiža could not enter the Stupizza valley in pre-glacial times, such that it had to flow towards the Soča, where large lakes had formed between Kobarid and Most na Soči. A later glacial phase would then have left moraines near Staro Selo, forcing the Nadiža to flow towards Stupizza. It is argued that the finding of Roman roads and necropolises in the Kobarid area exclude Kandler's hypotheses. In general, Marchesetti followed Gumprecht's ideas, but differed in the timing of the change of the hydrological system. According to him the Soča started to flow towards Stupizza at Robič as soon as the Soča glacier advanced into the Staro Selo valley.

Brückner (1891) also rejected Kandler's hypothesis. He praised Gumprecht for his insightful work and agreed with him that archaeological data prove Kandler wrong – a Roman floor was found in Robič and a Roman graveyard was unearthed near Kobarid, both showing that the palaeolandscape in Roman times was similar to today's. Brückner, however, also noted that the drainage divide near Staro Selo is almost exclusively formed by mass movement deposits from the Robič landslide, thereby disagreeing with Gumprecht.

Marinelli (1894) interpreted the Pradolino valley as a former course of the Nadiža/Natisone mainly based on observations on the morphology and the elevations of the past and present river courses. He stated that the abandonment of the Pradolino gorge must significantly pre-date the formation of the moraine that can be found in the Staro Selo valley (here he was citing Marchesetti, 1890, because he himself was not able to verify a moraine near Staro Selo). Due to backward incision, the Nadiža then occupied its present-day course. Marinelli also reported that the Pradolino valley exhibits W-dipping Triassic to Eocene strata and claimed that knowledge on the Friulian hydrography is still incomplete.

Tellini (1898) reported in detail on the glacial remains and lake deposits around Logje and Prossenicco, which testify to the Pleistocene glaciers having reached this area and to the fact that the present course of the Nadiža was once blocked by a glacier that created a glacial lake. According to him, sedimentological observations

indicate repeated glacial advances and retreats. Interestingly, Tellini remarked that this observation demonstrates the considerable length of the interglacial period, and he regretted that the lack of quarries does not allow a detailed paleontological study to prove his hypothesis. He regarded conglomerates found near Robič, Robidišče (ital. *Robedischis*), and Svino (ital. *Svina*) as preglacial and concluded that the Nadiža/Natisone occupied the Pradolino valley in preglacial times. Tellini stated that he follows the earlier ideas of Gumprecht (1886) and Marinelli (1894) that the Pradolino valley is a former course of the Nadiža/Natisone, which was occupied by the river when the Soča glacier blocked the main valley near Robič. The deep incision of the gorge led him to assume that it must have been occupied by the Nadiža/Natisone for longer times. The ideas of a long-lasting lake system between Most na Soči and Kobarid lacks geological evidence according to his observations. He mentioned that no moraines can be found in the Nadiža/Natisone valley south of Robič, which led him to assume that the incision of this valley is mainly post-glacial. Tellini also mentioned earlier observations by Taramelli (1870) that the Soča glacier reached at least until Robič and discussed the field observations of Gumprecht (1886). In Tellini's opinion, Gregorutti (1890) was too strict when stating there was never a connection between Nadiža and Soča. He also mentioned that glacial deposits in that area were depicted on the geological map of von Hauer (1868) and in the one that accompanied the publication of Gumprecht (1886).

Penck and Brückner (1909) rejected Tellini's (1898) hypothesis that conglomerates of the lower Natisone valley are of Villafranchian age and would, thus, testify to a ~Pliocene occupation of the Pradolino valley by the river. Instead, Penck and Brückner (1909) interpreted these deposits as typical "*Niederterrassenschotter*", i.e., from the Würm stage. Based on Kossmat's report of such terrace deposits near Logje (Kossmat, 1907, and private communication between Penck and Brückner and Kossmat) they argued that a glacier may well have blocked the present-day course of the Nadiža and led to drainage through the Pradolino valley. The limited amount of incision of the Pradolino valley near Stupizza allows drawing conclusions on the thickness of the glacier according to Penck and Brückner (1909) – the sediments would have been deposited on top of this glacier. Despite this, Penck and Brückner supported most of Tellini's ideas and applauded him for thoroughly referencing the available literature, but also stated that Tellini apparently missed Brückner (1891).

Feruglio (1929) briefly described the glacial system of the Soča glacier and its deposits around Prossenicco and Breginj (ital. *Bergogna*). He stated that the glacier blocked the valley and caused a glacial lake, and that the melt waters temporarily flowed through the Pradolino gorge.

The study area gained new attention several decades after these early works. For example, Tunis and Venturini (1987) detailed on the stratigraphy of the region and reported a section through the Pradolino valley, in which they mapped dip-slip faults striking ~70°, more or less perpendicular to the gorge. Later, Tunis and Venturini (1997) provided further details on the stratigraphy and the paleogeographic evolution, building upon their earlier works (e.g., Tunis and Venturini, 1984, 1986, 1987, 1992; Venturini and Tunis 1988, 1991, 1992, 1996).

Muscio & Zucchini (1997) briefly discussed the origin of the Pradolino valley and followed the interpretation of Marinelli (1894, 1912) and Cavallin & Martinis (1980), who regarded it as a paleo-course of the Nadiža/Natisone, which was later abandoned due to incision of the river into its current bed. They stated that the depressions at the base of the Pradolino valley are not only the results of karst phenomena (dolines) but that their formation was also related to the presence of faults that run ~perpendicular to the gorge, forming vertical steps in the strata.

In the same publication, Vaia (1997) dealt in detail with the geomorphology of the Pradolino valley. Although the text does not provide too much detail and individual observations, Vaia presented a six-step model for the evolution of the Nadiža/Natisone since the Pliocene, modified from Tellini (1898). First, in the Pliocene, a drainage divide existed between the Rio Bela and the upper course of the Nadiža; this ridge was connected to M. Mia and caused the Nadiža/Natisone to flow through the Pradolino valley towards Stupizza. The Rio Bela occupied what is now the Nadiža valley downstream of Logje but continued east towards Kobarid through the Staro Selo valley. Between M. Mia and Matajur another drainage divide existed in the valley south of Robič. Second, backward erosion led to drainage capture of the Nadiža by the Rio Bela system south of Logje. The Nadiža/Natisone abandoned the Pradolino valley (probably aided by normal faulting that caused NW-facing steps in the gorge) and flowed towards Robič, from where it continued towards Kobarid. Third, in a phase of glacial advance, the

Soča glacier blocked the Staro Selo valley all the way up to Podbela (ital. *Podbiela*) and caused a lake upstream. The Nadiža/Natisone re-occupied the Pradolino valley. The glacier's meltwater spilled over the drainage divide between M. Mia and Matajur, paving the way for the future Nadiža/Natisone. However, Vaia's figure includes a lake upstream of this drainage divide, indicating that he assumes it was only partially eroded. Fourth, when the glacier retreated beyond Robič, the Nadiža/Natisone again abandoned the Pradolino valley and had to flow south from Robič towards Stupizza and Pulfero. A lake was supposed to still have existed behind the former drainage divide between M. Mia and Matajur. Fifth, in the post-glacial phase, moraines remaining in the Staro Selo valley continued to block the old path of the Nadiža. Vaia assumed a lake persisted as the Nadiža was still partially dammed between Robič and Stupizza. Sixth, apparently showing the present-day configuration, the moraines in the Staro Selo valley now act as the watershed between the Nadiža/Natisone and the Soča systems. No lake exists south of Robič anymore.

Zendron (2018) summarized the research history of the Šuošterjova Jama, a cave ca. 3 km south of the Pradolino valley. She mentioned that the formation of the cave might have been aided by the erosive power of the Natisone. Citing Muscio et al. (1980), the author stated that the mouth of the Pradolino valley is ten metres above the location of the cave, and that the gorge is a former course of the Natisone.

Previous works compared with our model

The model that we developed in Diercks et al. (2021) is in line with the proposed six-stage evolution by Vaia (1997) based on Tellini (1898). We did neither include the location and extent of glacial lakes, nor did we work on the Pliocene course of the Nadiža/Natisone. The idea of a Pliocene paleo- Nadiža/Natisone that ran through the Pradolino gorge (Vaia, 1997, after Tellini, 1898) is attractive since it would remove the need for exceptionally high incision during the glacials as we have assumed in Diercks et al. (2021). In Vaia's view, the Pradolino valley was already established before the glaciations. However, this model would require significant erosion of the watershed near Logje to establish the present-day fluvial system. None of our own field observations is suitable to solve this question. We also concluded that the only possibility to form the wide valley of Staro Selo is that it was the pre-glacial course of the Nadiža.

Location of the Predjama Fault

The fact that we were kindly pointed to literature that we had not been aware of when writing Diercks et al. (2021) also raises the question if the north-western segment of the Predjama Fault runs through the Pradolino valley. The models of Vaia (1997) and earlier authors do not assume that the formation of the Pradolino valley was aided by tectonically weakened rocks in a fault zone underlying the gorge. We speculated that the Predjama Fault could probably run through the Pradolino valley, (i) because the valley is parallel to the general active fault trend in the area (Atanackov et al., 2021), (ii) because a morphological lineament can be seen on LiDAR data (similar to the trace of the fault as depicted by Moulin et al., 2014), and (iii) because the fault is drawn on several published maps. We did not map the fault in the field ourselves.

Kossmat's (1908) map shows a fault along the Pradolino valley, without further detailing its source. Fabiani et al. (1937) did not show a fault in their 1:100,000 geological map sheet Tolmino. Pirini Radrizzani et al. (1986, Fig. 19) drew a dashed line along the Pradolino valley in their map, indicating a potential or probably buried fault (*presunte o coperte*). These authors also showed a couple of short faults perpendicular to the Pradolino valley. The maps of Tunis & Venturini (1997) and Mocchiutti (1997) do not show a fault along the Pradolino valley, but the previously mentioned faults perpendicular to the gorge. Their studies relied on very detailed mapping of the area, during which a fault that manifested in sheared limestones likely would have been noticed. Carulli's (2006) 1:150,000 geological map of Friuli Venezia Giulia shows the Predjama Fault to run SW of the Pradolino valley and in a more westerly direction. The 1:250,000 geological map of Slovenia (Buser, 2009) shows a fault that enters the Pradolino valley from the northwest, parallel to the general strike of active faults in the region. Kokošin & Gosar (2013) did not mention the Predjama Fault in the area of Logje in their microzonation study. Moulin et al. (2014) suggested the Predjama Fault to run through the Pradolino valley. In Moulin et al. (2016), the north-western tip of the Predjama Fault lies at the entrance of the Pradolino valley near Stupizza.

If the Predjama Fault does not run beneath the Pradolino valley as indicated by most of the Italian studies, there is no reason to assume that the gorge developed due to an inherited weakness of the rocks. Instead, the erosive power of

the melt waters – and perhaps the paleo-Nadiža/Natisone – alone would be responsible for the spectacular incision.

Conclusions

Numerous studies published in Italian and German have dealt with the evolution of the Nadiža/Natisone and the Pradolino valley. After an intense debate in the late 19th and early 20th centuries, the model by Vaia (1997) after Tellini (1898) seems to be widely accepted. Our own conclusions drawn from field observations and geomorphological data are fully compatible with this model. If the Predjama Fault does not run through the Pradolino valley (see for example the detailed mapping of Tunis and Venturini, 1997), the idea that a former course of the Nadiža/Natisone created the proto-gorge (Vaia, 1997) seems plausible.

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