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Weathering properties of rock blocks and rock mass at natural heritage site Devils Town, Serbia

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Abstract

The Devils Town site in southern Serbia is a protected natural area where selective erosion is at work. More than 200 rock pillars, typically a few meters wide and up to 15 meters high, have formed within frail volcanic deposits subjected to long-term weathering. They are composed of tuffitic matrix and andesitic rock blocks of various sizes. The landscape is dominated by the pillars that are capped with such blocks, which are few dm to m across, as they offer better protection against the erosion agents. In this work, some index properties for reconstructing how weathering is distributed throughout the rock mass are determined, using several approaches. These were limited to non-invasive techniques due to the protected status of the site, including in-situ needle penetrometer tests and geophysical seismic profiling, as well as slake durability tests on solid rock samples from surrounding blocks that are equivalent to those atop the protected pillars. Surveillance and thermal footage was also used to determine the oscillation of the groundwater which occasionally appears at the interface of the andesite and tuffaceous matrix above. The obtained results suggest both zonal weathering into the depth, to about 3 m on average, but also some weathering effects of the rock mass in accordance with micro-location conditions and groundwater retention. Rock blocks on the other hand are expectedly relatively resistant to weathering, with slaking durability index I_{d2} and I_{d5} in a range of 0.98 to 0.94. Long-term weathering effects are also discussed in respect to contemporaneous erosion. This research contributes to the ongoing DEMONITOR project, and activities of the UNESCO Chair GeoHARM, and is yet to reveal important findings of the other aspects of this site, such as intrinsic geotechnical properties, columnar stability, nucleation of new landforms at adjacent sites, and more.

Keywords

Devils Town, Weathering, Needle penetrometer, Slake durability, Geophysical profiling.

1 Introduction

Erosional process is dependent on two factors, the atmospheric conditions or external forces on one hand, and rock material affected on the other.Rock exposed on the surface is weathered up to a specific depth, where in a regolith layer, with completely deteriorated parent rock structure and altered mineral/chemical composition, is sitting on top of the suprock layer. The suprock layer has preserved the initial structure of the parent rock but with changed mineral/chemical composition. Commonly, these two layers are referenced as topsoil, but some other features, such as limit compressive strength and behaviour under wet conditions are relevant in discerning between rock, soft rock and soil. The weathering develops differently in different climates, and indifferent rock types, but generally, on a time scale which is relatively long, i.e., hundreds and thousands of years. Scale of the neo-tectonic movements is usually of a next order of magnitude, thousands and millions of years (Marović et al. 2007), but nevertheless, these movements could be influential, primarily the vertical uplifts which are crucial for intensifying the erosion due to lowering of the erosional basis. The erosion affects the soil layer contemporaneously, as the soil is forming, with periods of intensification and stagnation, but it is safe to estimate that the age of soil can be in some correlation with the dynamics of the dominant erosional process. There are techniques for precise dating of the soil and the erosional process age, based on radioactive isotope or cosmic nuclide amounts, but for general estimations, determining depths and estimating rates using geological evidence is sufficient.

In this work, the weathering properties are observed and related to the genesis of a rock formation located at a badlands site called the Devils Town in southern Serbia (Fig. 1) on the slopes of the Radan Mt. This is a site made of volcanic rock susceptible to superficial denudation and rill erosion, but with some peculiarities. Within the tuffaceous mass and on top of it, large rock fragments made of altered andesite are hosted. Such disposition is causing selective erosion to act, so that more resilient parts, protected by andesite blocks, are eroding at slower rate than frail tuffaceous matrix (Marjanović et al. 2024). The present task is to estimate how weathering affects both the rock matrix and andesitic blocks within, and how it changes spatially throughout the formation.

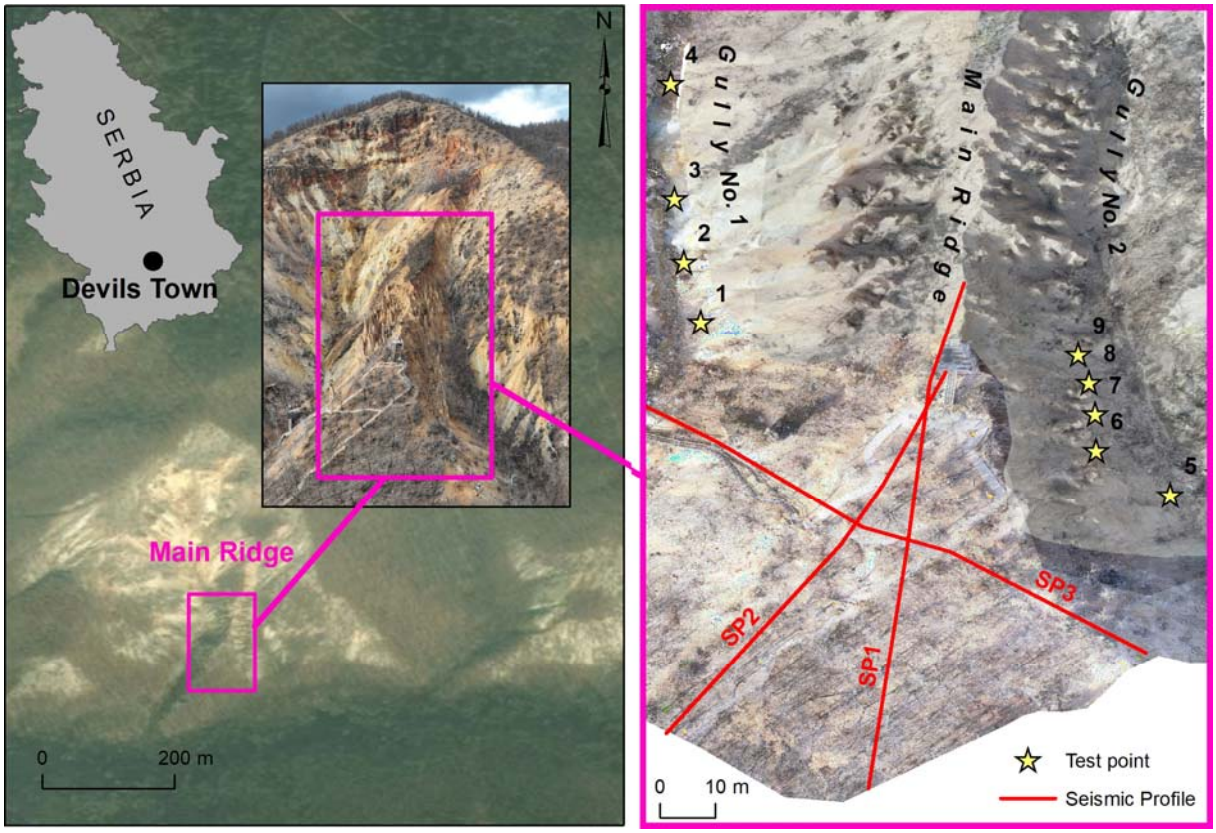


Fig. 1 To the left: setting of the area of interest with reference to location in Serbia, wider area of the Radan Mt. orthophoto and perspective view of the main ridge in the incept (purple square); To the right: a detail of the main ridge site with investigation works displayed(seismic profiles SP1-3 and needle penetrations 1-9).

2 Methodology

To establish weathering properties of the andesitic blocks and the cementing matrix, several field and laboratory techniques were employed:

- *in situ* needle penetrometer testing to determine the relative compressive strength difference around the contour of the site;
- geophysical seismic profiling to determine the depth and structure of the weathering zones beneath the surface, using the p-wave velocities;
- slake durability testing to determine the resistivity of the cap rocks in laboratory conditions;
- visual monitoring using a fixed surveillance camera and thermal camera for zoning of weakened deposit zones, affected by percolating water and drying.

The penetrometer testing included systematic field survey along the base contour of the main ridge (Fig. 1). Portable SH70 Maruto penetrometer was used with standardized nomogram for converting applied force vs. penetration depth into compressive strength (Ulusay & Erguler 2013). Testing points were distributed around the ridge base, facing the adjacent gullies. The sampling was limited to an accessible height of 1.5 to 2.0 m. The penetrations were performed in the pillar bodies, targeting fine particle matrix, i.e., avoiding andesitic fragments larger than 2 mm. A total of 36 tests were performed successfully, whereas locations with no penetration after exceeding the maximum piston force of 100 N are noted.

Seismic profiling was performed along and across the main ridge line (Fig. 1), using standard dispositions with spacing between geophone gauges ranging between 2 – 3 m, depending on the estimated local depth. In effect, 3 seismic profiles along the main ridge line ranging from 50 – 120 m were completed using mechanical (10 kg hammer) triggering of the central point between each geophone pair, totalling 11-13 triggers per profile. The geophone spacing was adjusted to capture sufficient depth with optimal resolution and included 2, 4 and 5 m variants.

Slake durability testing was performed using the standard two-barrel lab equipment (Franklin & Chandra1972), high precision scales (sensitive to 10^{-3} g) and standard drying oven for 105°C drying cycles. Instead of the standard 2-cycle slaking, 5-cycle tests were performed, to reach a better insight into long-term weathering, given that petrographic analysis have confirmed presence of secondary clay minerals due to argillic alterations of the parent andesite.

Visual monitoring was conducted using a solar-powered HD camera. Scheduled capture was set to acquire high-definition video at 12:00 to 12:15 every day, from the 24th of April 2024 until the 20th of March 2026, with several technical breaks due to low battery or connection issues. Captured print-screens were used to distinguish the wet and flowing zones of the ridge base. In addition, thermal camera FLIRone, with 80x60pixel resolution, single focal point and accuracy of ±3 °C was used occasionally, during the field visits to capture wider scenes to enclose most of the upper ridge line. It was used for distinguishing between dry and wet zones of the formation.

The approach included determining weathering potential and differentiation of formation's weathering zones on surface and at depth (horizontally and vertically). Such interpretation can be used to discover the principal erosional pathways and development of the process in the future, but it also makes a reference for erosional past dynamics.

3 Study Area

The study area is located in southern Serbia, on the slopes of the Radan Mt. near the Prolom Spa. It encompasses a natural heritage site with distinct geomorphological features situated within the Lece volcanic complex, predominantly consisting of andesitic and volcaniclastic deposits formed between the upper Oligocene and late Pliocene (Malešević et al. 1978). The site includes 209 pillar-like forms, reaching heights of up to 15.1 m and diameters of around 4.15 m, which are typically capped (45% of them) by more resistant rock blocks playing a critical role in their preservation from the rainfall flush (Marjanović et al. 2025).

The structure of the deposit is irregular and possibly linked to high-density pyroclastic or debris flows mobilized during and after its genesis. During deposition, complex interactions between the hot, dense matrix and the embedded rock fragments led to a redistribution of particle sizes, resulting in inverse

grading where larger boulders migrated toward the upper portions of the deposit. Following cooling and partial cementation, these blocks acted as protective caps. Over time, differential rill erosion selectively removed the surrounding frail and weathered material, leaving behind the present-day pillar morphology.

The formation can be considered as a unique material, best described as Block-In-Matrix (BIM) rock, but it essentially comprises of two components, the andesitic blocks and tuffaceous matrix (Fig. 2). The blocks, which vary in size and shape, but mostly have elongated axes, are composed of altered andesite, hydrothermally bleached. Apart from original hornblende and plagioclase with seldom quartz phenocrysts, it alco contains secondary interstitial quarts jets and several alteration minerals, such as argillite, pyrophyllite, alunite, sericite, etc. suggesting acidic and hot conditions during alteration. The matrix on the other hand has even higher clay content, as indicated in sieving tests with 25% of fines (Fig. 2),and the X-ray diffraction analyses with distinct spikes of several clay minerals, such as kaolinite, illite and smectite. This difference between altered but not much weathered blocks vs. highly weathered matrix suggests a remobilization of the original deposits, that could have been multi-staged.

The site remains highly dynamic, with ongoing erosion processes driven by precipitation, surface runoff and weathering, resulting in continuous changes of the existing and formation of new pillars. Weathering is particularly important, as it directly governs further erosion paths.

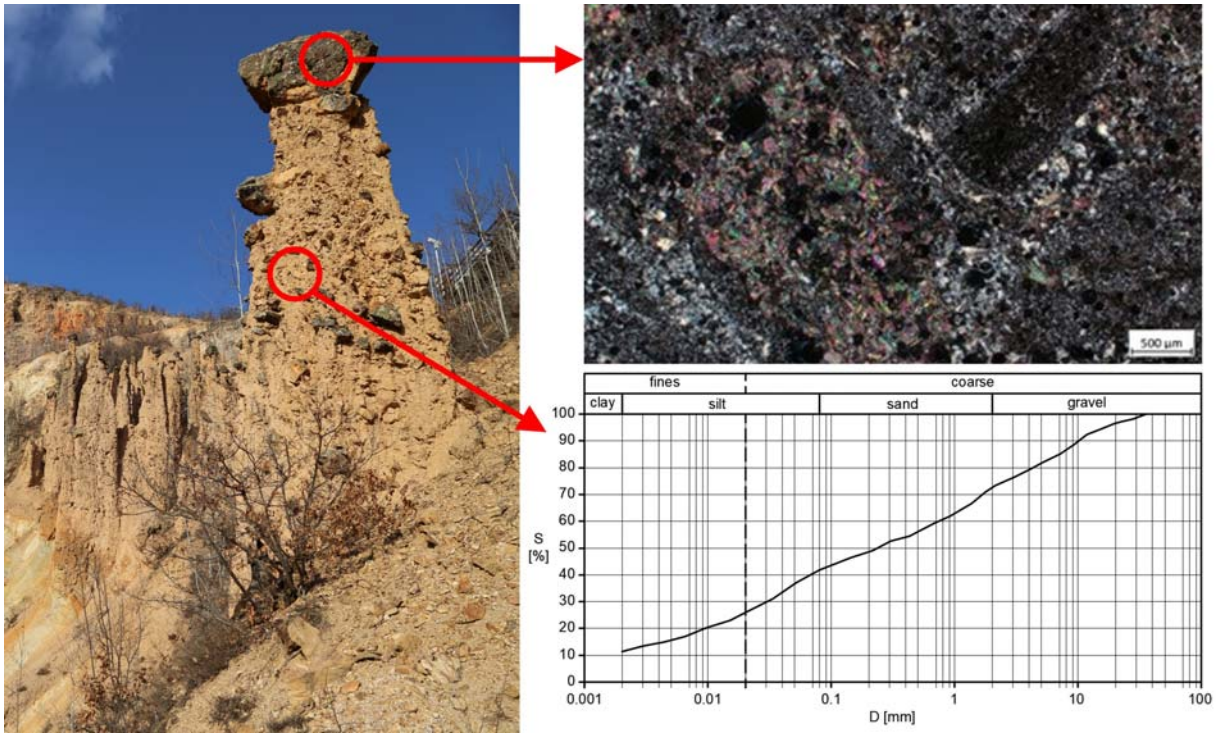


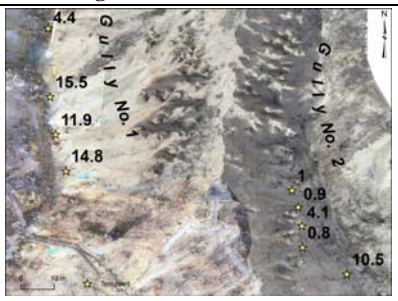
Fig. 2 To the left: typical landform from the Devils Town site; To the upper right: petrographic thin section of the altered andesitic block (pyrophyllite and quartz jets in focus, with crossed Nikols); To the lower right: particle size distribution of the tuffaceous matrix (flat and relatively uniformly distributed curve, wherein *D* is sieve aperture and *S* is residue percentage).

4 Results and Discussion

The evolution of Devils Town reflects an imbalance between material formation and erosion processes. The erosion rate is by far quicker and targets the frailest material. In effect, the landforms are created selectively across the main ridge by deepening of their base. Needle penetrations can be used as a proxy to reveal the spatial patterns of weathering. The testing was not performed in the upper part of the main ridge due to the protected status of the landforms and restricted access to their base and remained focused on the accessible parts of two gullies from each side. Spatial distribution of the weakened zones (Table 1) suggests that the weathering pathways are already established and that the matrix material has higher compressive strength in the Gully No.1, in contrast to the Gully No. 2, whereas values are slightly decreasing toward north, i.e., in a direction where exposure to the surface is increased (poor or no vegetation) and the rill energy is likely higher. The pattern indicates that the weathering process is developing downslope along the ridge line and perpendicular to it. In support of

this view, the slope toward the Gully No. 2 is slightly steeper, and landforms are shorter and thinner in diameter (Marjanović et al. 2025).

Table 1. Needle penetration (SH70) results.

Testing point	**Force vs. penetration depth (N/mm)**	***UCS* values* based on SH70 (MPa)**	**Spatial distribution of UCS along the main ridge base**
1	63.3	14.8	
2	50.5	11.9	
3	66.7	15.5	
4	16.1	4.4	
5	44.5	10.5	
6	2.4	0.8	
7	15.6	4.1	
8	2.75	0.9	
9	3.1	1.0	

*correlation based on Ulusay&Erguler 2013

Rock blocks, which also had to be sampled outside the restricted area (no actual rock cap was sampled, but toppled blocks laying on the foot of the slopes above the gullies) show good resilience to slaking after 2 cycles, despite the presence of clay minerals and can be classified as *Extremely High* (Table 2). As expected, the slake durability index I_d remains above 90%, even after the 5th cycle, but the drop between the standard I_{d2} and I_{d5} for additional 2% on average lowers the category to *Very High*. Rounding of the sample fragments becomes noticeable after 5 cycles, for example apparent for fragments 1, 4, 5 and 9 in sample number 3a (Table 2).

Table 2. Slake durability test results.

Sample No.	I_{d2}	I_{d5}	**Sample No. 3a after the 2nd cycle**	**Sample No. 3a after the 5th cycle**
1a	0.96	0.94		
1b	0.97	0.95		
2a	0.98	0.97		
2b	0.97	0.95		
3a	0.97	0.95		
3b	0.98	0.96		

Pedogenic studies indicate that the transformation of rock into soil within the critical zone is inherently slow, with parent material and chemical weathering rates typically ranging 0.004–0.4 mm/year, and 0.01–0.1 mm/year, respectively (Stockmann et al. 2011). Also, it does not necessarily involve linear trend but rather logarithmic, because the process normally decelerates as the soil layer thickens over the years. Finally, climate, vegetation conditions and land use can drastically change over such large time scales and affect the trend, but for the sake of simplicity, it seems justifiable to adopt the linear formulation. At material scale, the progressive weakening of volcanic rocks further contributes to this behaviour. Weathering studies of andesitic material show that chemical alteration leads to increased porosity, mineral transformation, and development of mechanically weakened outer zones (Colman 1982). This implies that both the volcanoclastic matrix and the protective andesite caps undergo gradual strength reduction over time. Consequently, the caps cannot be considered permanent stabilizing elements, but transitional features whose integrity can be affected through the ongoing weathering.

If combined maximal weathering and chemical decomposition rate of 0.25mm/year is adopted (an average of 0.1 and 0.4 mm/year) as a proxy for weathering velocity, the total amount of time needed for formation of the regolith/suprock can be estimated if its depth is known. Depth can be revealed by drilling, pitting or trenching, but due to the protected status of the site, invasive techniques were avoided. Instead, seismic refraction along specified profiles was conducted on the surface of the lower ridge crest, which is still blanketed with the topsoil (unlike the upper part of the ridge which is already caught by selective erosion). The averaged soil profile based on p-wave (*Vp*) velocities (Fig. 3) under assumption of relatively stationary conditions (except for anticipated neotectonic uplift) suggests that regolith/suprock layer is about 3 m deep. This means that it took at least 12,000 years for this layer to be formed by the weathering of the parent tuffaceous matrix. At least one order of magnitude is the

anticipated age of the erosional process, i.e., 1.200 years or slightly less, given that neotectonics uplift of the entire Radan Mt. block, which is averaging 15.3 mm/year (since the onset of the Alpine orogenesis about 65 M years ago), the erosional process is additionally accelerated. Finally, the presence of groundwater which soaks the base of the formation, as it cannot percolate through the impermeable altered andesite beneath, is also a factor in the weathering process. The hight varies over the year, and is most apparent after the heavy rainfall events, but on average it can be zoned to the height of about 3.2 m from the andesite/tuff interface. This time, the effect direction is downward along the ridge strike but also uphill to water table limit (Fig. 3). This means that the weathering is likely ongoing from both sides of the tuffaceous layer and compromises the stability of the landforms from the base up and from the top down.

A study conducted in clay-rich badlands of Central Italy reports spatial and temporal variability of denudation rates, with long-term averages reaching 1–2.5 cm/year, and short-term values up to 3–4 cm/year, or higher under localized conditions. An important denudation characteristic highlighted in this study is the discontinuous, event-driven pattern, with extended periods of relative stability compromised by rapid erosion episodes triggered by specific environmental conditions (Della Seta et al. 2007).Current estimation for the Devils Town site is 2 cm/year on average, but it yet needs to be confirmed, when the monitoring campaign ends.

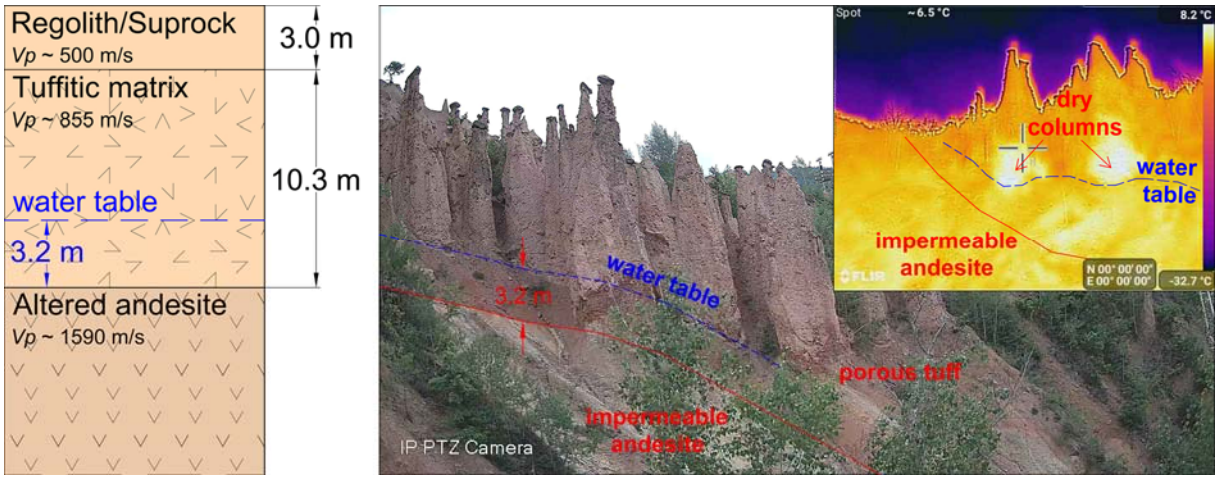


Fig. 3 To the left: the averaged soil profile; To the right: surveillance footage on a rainy day with apparent water table level (in the incept a thermal image revealing dry and wet conditions).

5 Conclusion

In this work, the weathering has been quantified indirectly, through various index properties obtained by field and laboratory tests. These have confirmed the anticipated pathways of erosional preference along the main ridge site at the protected Devils Town landmarks. Coupled processes of weathering and subsequent/contemporary erosion are forming but also destabilizing these rare columnar landforms. The combined effects of these processes and mechanisms indicate that the stability of the pillar formations is temporary. Weathering conditions continuously reduce material strength, while episodic erosion removes weakened material at rates that exceed its production. Once the protective caps are destabilized, rapid degradation of the exposed columns follows, leading to the eventual collapse. The observed morphology can therefore be interpreted as a transient equilibrium state. Weathering is focused primarily on the tuffaceous matrix layer. In vertical direction, the weathering is progressing from both directions, top-down due to the standard atmospheric and percolating water influence, but also bottom-up, due to the groundwater occurrence. The general horizontal direction of the weathering process is from the hilltop downward along the ridge line, and is apparently asymmetric between the two gullies, making the Gully No. 2 more susceptible. The erosion patterns follow these pathways but have strong selective nature, due to the randomly dispersed andesitic rock blocks on top and throughout the tuffaceous matrix. The timescales of the weathering and erosional processes are likely different for one order of magnitude ranging about 10k to 1k years, respectively. Further investigations are essential for determining the overall geotechnical properties of the rock mass and estimating the long-term stability conditions. Monitoring campaigns that are still ongoing,

will provide the answer to the current and past erosional rate, and help predict the stability conditions of the landforms in the future, as well as their lifespan.

6 Acknowledgement

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