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Correspondence: Challenges with dating weathering products to unravel ancient landscapes

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K-Ar dating of illite (clay) in weathered bedrock (saprolite) is an exciting but yet incompletely understood new application of the K-Ar dating method that can potentially provide valuable information about the evolution of landforms and continental isostasy. Fredin et al.[1] use this approach in an attempt to date the strandflat in coastal western Scandinavia. Based on K-Ar illite ages from three widely separated localities in the North Sea (Utsira High), West Norway (Bømlo), and southern Sweden (Ivö), they suggest a Late Triassic (~210 Ma) age for the strandflat. However, when employing such a new methodology, it is particularly important to carefully consider the results together with existing data, and Fredin et al.[1] neglect previously published radiometric, stratigraphic, and geomorphic constraints that strongly suggest that the current strandflat erosional level in western Norway is younger than Triassic.

The discovery of Late Jurassic (Oxfordian) sediment caught up in a fault zone in Proterozoic bedrock near Bergen north of Bømlo (Fig. 1) revealed that rocks in the strandflat area were at or near the surface at ~160 Ma[2], opening the possibility that the strandflat may contain Mesozoic elements[3]. Offshore, the crystalline bedrock surface is seen as a remarkably planar geomorphic feature on seismic data, preserved under Jurassic sediments (offshore part of Fig. 1b). However, this surface is dipping to the west by ~5°, while the strandflat is almost horizontal (onshore part of Fig. 1b; also shown in Fig. 6 in Fredin et al.[1]), clearly cutting into the Middle Jurassic paleosurface and thus mainly shaped by younger (post-Middle Jurassic) processes. From geometric considerations, it is therefore quite unlikely that the samples from the Utsira High and Bømlo represent the same weathering surface.

Fredin et al.[1] claim to be able to constrain the age of the strandflat along the west coast of Norway by dating illite in weathered bedrock. However, K-Ar dating of illite to constrain weathering ages is previously untested; all previous studies cited by Fredin et al.[1] use K-bearing manganese oxides or alunite-group sulfates. Hence, such K-Ar illite weathering ages should be interpreted with care and in the framework of independent data, which in this case include low-temperature thermochronology (fission track and (U–Th)/He ages), the offshore stratigraphic record, structural aspects, and the estimated depth of dike intrusions, as briefly summarized below.

A significant quantity of fission track and (U–Th)/He data has recently been published from the strandflat area[4]. Such ages date the cooling of the currently exposed rocks through the partial annealing/retention zone of the respective system, which is 210–140 °C for the zircon (U–Th)/He system, 120–60 °C for the apatite fission track (AFT) system and 70–40 °C for the apatite (U–Th)/He system. All such ages should be older than the age of any preserved in situ weathering products. A regional compilation of AFT ages from Scandinavia[5] shows that AFT ages from the entire Norwegian strandflat area are similar to or, more commonly, younger than the ~210 Ma illite ages reported by Fredin et al[1]. Most ages from the strandflat region relatively near their Bømlo locality show early to middle Jurassic (200–160 Ma) AFT ages[4] (Fig. 1a). These ages roughly indicate that the samples were buried at >2 km depth in the Early Jurassic, assuming a thermal gradient of 30 °C/km. (U–Th)/He zircon data from the same area of ~225 Ma[4] suggest burial of the present strandflat level to >4 km depth in the Late Triassic. These data are consistent with paleomagnetic analysis of Permian (~250 Ma) dikes in the strandflat area north of Bømlo, which suggests that the dikes were emplaced at ambient temperatures between 150–500 °C (5–15 km depth)[6].

In slowly cooled basement terranes like western Norway, it can be misleading to reconstruct the exhumation history based on fission track ages alone. More precise and detailed cooling paths can be derived from inverse time–temperature modeling. The resulting models, presented by Ksienzyk et al.[4], consistently show cooling throughout the Triassic and into the Jurassic, with post-Jurassic burial and new exhumation for coastal samples (Fig. 2, blue curves). In order to test for potential Late Triassic weathering, we remodeled strandflat samples by imposing constraints to bring them to the surface in the Late Triassic (green box in Fig. 2). With this constraint, most models showed a significantly

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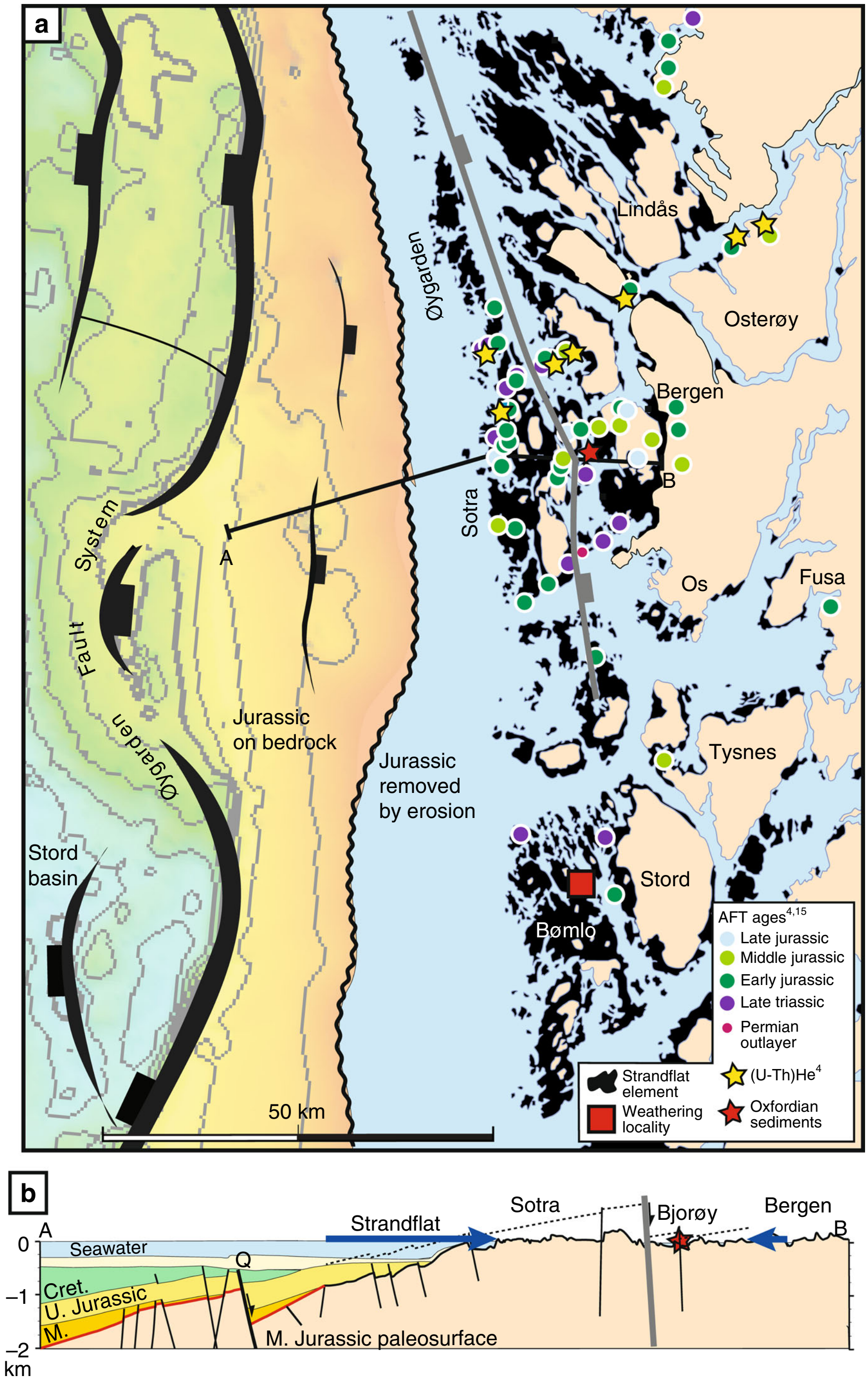

Fig. 1 Map of and cross-section through the strandflat. **a** Map of the strandflat area in SW Norway, and offshore fault and top basement map. The erosion line marks the eastern boundary of Jurassic sediments on basement. Red square marks sampling locality by Fredin et al.[1] (Bømlo). AFT localities (from Ksienzyk et al.[4] and Kohlman et al.[15]) are color-coded with respect to age. **b** Cross-section[2], showing the west-dipping Jurassic paleosurface buried under Middle and Late Jurassic sediments and cut by the strandflat near sea level

reduced fit with the data. More specifically, cooling paths with a good fit that are supported by the data (good paths) were not obtainable, only paths with a lower fit that are merely “not ruled out by the data”[7] (so-called “acceptable paths”; red curves in Fig. 2). Furthermore, those acceptable paths involve unrealistically rapid cooling, implying almost instantaneous exhumation from ~3 km depth to the surface around 220 Ma (Fig. 2, red curves). Thus, the present thermochronologic data set does not support a Late Triassic weathering scenario.

Looking at the stratigraphic record, the offshore Jurassic basement paleosurface is abruptly offset by the major North Sea rift-bounding Øygarden Fault System, which bounds the Stord basin and it is up to 4–5 km of Triassic-Jurassic clastic sediments to the west[8] (Fig. 6 in Fredin et al.[1]). A significant part of these sediments is late Triassic-Jurassic, and the basin geometry suggests a proximal onshore source[9]. Hence, removal of considerable amounts of bedrock in the coastal area of SW Norway through the Triassic-Jurassic, as suggested by low-temperature

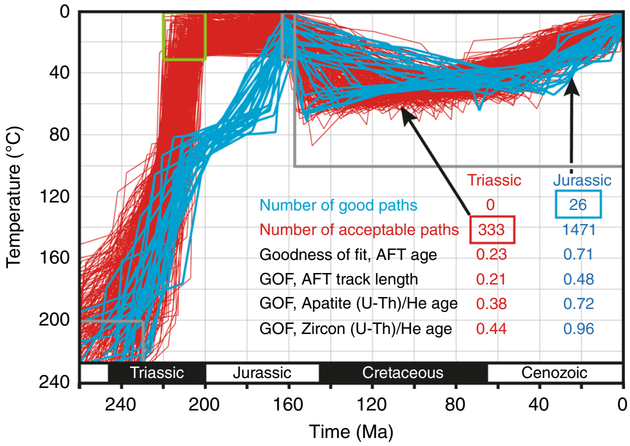

Fig. 2 Time-temperature paths. The paths are derived from AFT and apatite and zircon (U-Th)/He data (sample BG-113 in Ksienzyk et al.[4]). Red lines are 333 acceptable-fit paths, where the sample was forced to the surface in the Late Triassic and kept there until the Late Jurassic. Blue lines are good-fit paths, where the sample was brought to the surface in the Late Jurassic (the 1471 acceptable paths for this model are not shown). The latter model is favored because it produces many more acceptable paths and also many good paths, while the first case (red) produced no good paths. Gray boxes indicate constraints for both models, while green box applies only to Triassic surfacing (red) model

thermochronologic data referred to above, is consistent with the offshore stratigraphic record.

Finally, faulting in the strandflat region and immediately offshore SW Norway occurred over a long time period, and includes late Jurassic-early Cretaceous activity[10,11] with local offsets of up to several hundred meters[12] (Fig. 1). However, the strandflat is not affected by such offsets, suggesting that its formation or completion occurred after the late Jurassic.

In summary, Fredin et al.'s K-Ar illite dates and their implications for landscape evolution in western Scandinavia should be reconsidered in the light of independent constraints, which consistently show that the strandflat is unlikely to be as old as Triassic. We do not attempt to reinterpret their isotopic data here, but raise the question whether their Triassic illites at the Bømlo locality may have grown in a subsurface fracture system prior to exhumation, as reported recently for a close-by locality by the same research group[13]. As for the offshore Utsira data presented by Fredin et al.[1], they are in agreement with recent zircon (U-Th)/He, AFT and apatite (U-Th)/He dating that shows that the basement surface in that particular structural high reached near-surface temperatures in Carboniferous-Triassic times[14]. However, there is no reason to believe that these two surfaces should be of the same age, as the top basement surface in the northern North Sea basin is well known to be diachronous throughout the basin. We believe that the interesting post-Caledonian history of western Scandinavia can be understood only through an integrated effort that takes all available data into account, and urge the authors to critically reconsider their interpretations accordingly.

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Author contributions

The initiative, selection of data, main writing, and building of the structure of this contribution was by the first author (H.F.). An important part of the contents builds on low-temperature thermochronologic data that were collected and analyzed primarily by A.K., with all current authors as contributors. A.K. further contributed by remodeling some of the published geochronologic data, which resulted in Fig. 2. All authors contributed to the text.

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Correspondence: Reply to 'Challenges with dating weathering products to unravel ancient landscapes'

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As the title of the correspondence by Fossen et al.[1] suggests, determining the age of landscape elements of the Earth surface is difficult. We thus welcome the opportunity to clarify our arguments on the contentious themes touched upon by Fredin et al.[2] The age of landscapes has been a recurring research topic for the last century. Often, landscape ages can be deduced indirectly through morphostratigraphic correlations leading to relative chronologies. However, when working in geological contexts where a sedimentary cover is not present[1], and the traditional geochronological tools are not suitable, not only are absolute dates of etch surface formation essentially impossible to obtain, but even relative chronologies are challenging. In an attempt to circumvent this problem, we have applied an untested methodology to date pockets of weathering products at three different sites in Scandinavia (Ivö southern Sweden, Utsira High offshore Norway, Bømlo west Norway) by K-Ar dating of illite formed authigenically during the weathering of the crystalline host rock[2]. Our results support weathering in the Late Triassic at all studied localities.

We note that Fossen et al.[1] do not significantly question our results at two of the investigated localities (Ivö and Utsira High), where there is stratigraphical control on the age of weathering. This selective approach is questionable because the three dated sites are internally consistent with each other, of which two have independent stratigraphical control of the Triassic age of weathering. The utility of the new method should thus be discussed including the whole data set from all dated sites.

We start our rebuttal from the concluding remarks by Fossen et al.[1], who question the saprolitic origin of the dated outcrop on Bømlo, suggesting that we might have dated a Triassic fracture. We firmly reject this possibility. Mesoscopically, the investigated outcrop lacks any evidence of a 'structural origin' of the dated clay-rich material. Comparison with many fractures and brittle deformation zones in the surrounding excludes that the dated illite results from synkinematic authigenic growth during faulting[3]. More telling, the detailed XRD analysis of clays in three samples from a traverse across the saprolitic outcrop documents clay assemblages that are typical for chemical weathering (Table 2, Fredin et al.[2]). We already showed that the sample closest to the fresh bedrock exhibits a less mature clay-weathering signature, whereas the sample farthest away from the fresh host rock contains a higher concentration of mature weathering products, such as kaolinite, and lower contents of immature clays such as smectite[2]. This spatially controlled mineralogical pattern is consistent with rock alteration through chemical weathering and not a faulting, fracturing or hydrothermal origin. Here, we further reinforce this interpretation by comparing the clay mineralogy of a nearby fault (the Goddo Fault, studied in detail by Viola et al.[4]) with that of the dated saprolite outcrop. The Goddo Fault phyllonitic sample BO_GVI_2 contains illite/mica and interstratified illite-smectite, with only subordinate kaolinite (Fig. 1a). The clay-rich sample BO_GVI_1 from the fault core also contains a similar clay mineralogy (Fig. 1a), but with dominant interstratified illite-smectite. In contrast, the saprolitic sample closest to the hosting fresh granodiorite (sample 'Bømlo 2' in Fig. 1b) is dominated by smectite with subordinate illite and kaolinite. The central portion of the saprolite outcrop (samples 'Bømlo 3' and '4'), instead contains predominant kaolinite, an end-member product of weathering. Importantly, samples from the weathering profile still preserve in situ primary mineral textures and grains from the host rock, although the rock is sufficiently altered through chemical alteration to easily disaggregate when manipulated by hand. In addition, the outcrop-bounding bedrock joints exhibit a rounded morphology consistent with the fact that weathering first attacks

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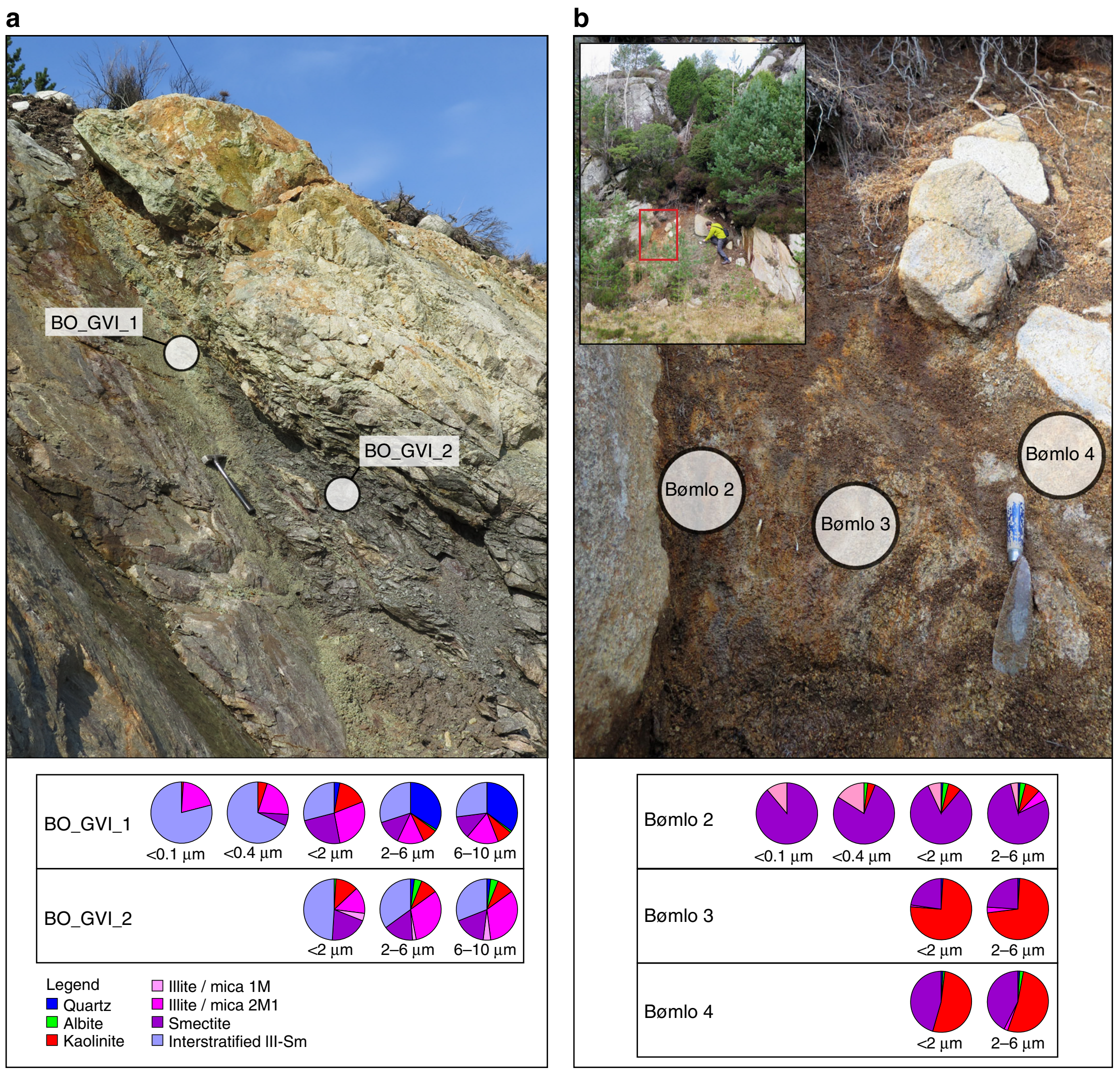

Fig. 1 **a** Picture and XRD clay mineralogy from two fault gouge samples analysed at different grain size fractions sampled at the Goddo fault on northern Bømlo. For a detailed description of the fault anatomy and samples, see Viola et al.[4] **b** Picture and XRD clay mineralogy from three saprolite samples analysed at different grain size fractions. The inset shows an overview of the outcrop, with red box outlining the main image (sampling site). Trowel is 20 cm long. The person (O.F.) sits at a core boulder covered with a thin veneer of glaciomarine diamicton likely of late-glacial age, which indicates that the outcrop has survived glacial overriding. The sediment-covered section was not sampled. Note that primary bedrock grain/texture is still present in the saprolite, although oxidised (rust-coloured). Grey/white portions around sample 'Bømlo 3' consist of kaolinite clay. For additional details, see Fredin et al.[2]

sharp edges, a process that produces conspicuous core boulders ('woolsack morphology'). In summary, we remain confident that the dated samples from Bømlo are saprolitic in origin and that, therefore, the obtained ages reflect weathering.

Fossen et al.[1] stress that available low-temperature geochronological (LTG) data in western Norway indicate that the present strandflat level was buried down to depths of >4 km in the Late Triassic and >2 km in the Early Jurassic, requiring that K-Ar ages of weathering products should be younger than any LTG data. We agree but note that available LTG data in the study area exhibit a large scatter with ages ranging from Middle Triassic to Late Jurassic[1, 5]. Furthermore, Utami[6] reports seven apatite fission-track ages from the Bømlo area varying within very short distances between 227 and 165 Ma. In addition to this variability, we also note that important criticism by Fossen et al.[1] are based on the age and thermal modelling (with only limited time-temperature paths; Fig. 2[1]) of one single sample (BG-113, Ksienzyk et al.[5]) from Sotra, ca. 50 km north of the sampled saprolite locality on Bømlo. Sample BG-113 suggests that subaerial exposure of the strandflat level on Sotra is unlikely in the Late Triassic[1, 5]. On the other hand, thermal modelling by Utami[6] (whose results are also heterogeneous and vary from sample to sample) indicates that temperatures of 20–60 °C were locally attained in the Late Triassic, which agrees with near surface conditions and possible saprolite formation in Bømlo at that time (e.g., sample JN-06, close to the dated saprolite;[6] Fig. 4.10 in Utami[6]). It has to be stressed that saprolite and saprock can form in a spatially heterogeneous manner down to great depths (up to several hundred meters) under extreme tropical conditions on tectonically stable cratons, implying that LTG and weathering K-Ar illite age data might converge. The kinetics of illite growth in saprolite is unknown, but is presumably geologically fast, making the system more sensitive to evolving geological processes than regional cooling/exhumation. It is likely that what is now Scandinavia was affected by severe hot-house conditions in the Late Triassic-Early Jurassic[7, 8], and that we sampled the deepest section of a saprolite profile that might have been tens to hundreds of meters thick before subsequent stripping. We thus suggest that also LTG data from this area should be interpreted with caution and tested against independent results.

We point out that correlating denudation surfaces on and offshore using topographic profiles is controversial, as highlighted by the recent debate on palaeolandscapes in Scandinavia[9, 10]. One needs to be cautious when assigning relative landscape ages based on differences of ~5° in dip between the sub-Middle Jurassic denudation surface offshore and the present strandflat onshore, especially in the light of the local obvious post-Triassic faulting and block tilting[11]. The dipping sub-Middle Jurassic palaeosurface might well have attained its dip due to offshore faulting and differential subsidence upon sediment loading.

While the results of Fredin et al.[2] might not fully constrain the age and complex genesis of the strandflat, the published data yield a maximum Mesozoic age for its initial formation. We conclude that the strandflat was initiated in the Mesozoic (as also suggested by Fossen et al.[1], who wrote that the strandflat 'may contain Mesozoic elements'), rather than completely in the Pleistocene, as indicated by early investigations[12]. We maintain that strandflat genesis at Bømlo is multi-genetic and multi-episodic, and deep weathering in the Mesozoic facilitated extensive Pleistocene erosion[13–15].

Data availability. The authors declare that the data supporting the findings of this study are available within the paper.

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Author contributions

O.F., G.V. and A.Ma. wrote the text with input from all the co-authors. O.F. and A.Ma. drafted the figure.

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