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HAL Id: hal-00590894
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Submitted on 16 May 2013

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Dating inset terraces and offset fans along the Dehshir fault combining cosmogenic and OSL methods

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Abstract

\(^{10}\)Be and \(^{36}\)Cl cosmic ray exposure (CRE) and optically stimulated luminescence (OSL) dating of offset terraces have been performed to constrain the long-term slip-rate of the Dehshir fault. Analysis of cosmogenic \(^{10}\)Be and \(^{36}\)Cl in 73 surface cobbles and 27 near-surface amalgams collected from inset terraces demonstrates the occurrence of a low denudation rate of 1 m.Ma\(^{-1}\) and of a significant and variable inheritance from exposure prior to the aggradation of these alluvial terraces. The significant concentrations of cosmogenic nuclides measured in the cobbles collected within the riverbeds correspond to 72 ± 20 ka of inheritance. The mean CRE age of the surface samples collected on the older terrace T3 is 469 ± 88 ka but the analysis of the distribution of \(^{10}\)Be concentration in the near-surface samples discard ages older than 412 ka. The mean CRE age of the surface samples collected on terrace T2 is 175 ± 62 ka but the \(^{10}\)Be depth profile discard ages older than 107 ka. For each terrace, there is a statistical outlier with a younger age of 49.9 ± 3.3 ka and 235.5 ± 35.4 ka on T2 and T3 respectively. The late sediments aggraded before the abandonment of T2 and inset levels, T1 b and T1a, yielded optically stimulated luminescence (OSL) ages of respectively 26.9 ± 1.3 ka, 21.9 ± 1.5 ka, and 10.0 ± 0.6 ka. For a given terrace, the OSL ages, where available, provide ages that are systematically younger than the CRE ages. These discrepancies between the CRE and OSL ages exemplify the variability of the inheritance and indicate the youngest cobble on a terrace, that minimizes the inheritance, is the most appropriate CRE age for approaching that of terrace abandonment. However, the upper bound
on the age of abandonment of a terrace that is young with respect to the amount of inheritance
is best estimated by the OSL dating of the terrace material. For such terraces, the CRE
measurements are complementary of OSL dating and can be used to unravel the complex
history of weathering and transport in the catchment of desert alluvial fans. This
comprehensive set of dating is combined with morphological offsets ranging from 12 ± 2 m to
380 ± 20 m to demonstrate the Dehshir fault slips at a rate in the range 0.9 mm.yr\(^{-1}\) - 1.5
mm.yr\(^{-1}\). The variable inheritance exemplified here may have significant implications for
CRE dating in arid endorheic plateaus such as Tibet and Altiplano.
1. Introduction

The Dehshir fault is a 380 km-long, strike-slip fault cutting through the Central Iran plateau, north of the Zagros. It is located between 29.5°N-54.6°E and 33°N-53.1°E and is part of a series of N-striking dextral faults slicing Central and Eastern Iran (e.g. Berberian, 1981). The total offset of the fault, denoted by the geological offsets of the Nain Baft suture and the Urumieh Doktar magmatic arc, amounts to 65 ± 15 km (Inset Figure 1; Walker and Jackson, 2004; Meyer et al., 2006). The southern portion of the Dehshir fault that runs across a series of Quaternary alluvial fans shows clear evidence of recent right-lateral motion (Figure 1). Geomorphologic studies have been performed to estimate the slip-rate of the fault. Combining cumulative offsets of gullies and terrace risers with their inferred Holocene age, Meyer et al (2006) and Meyer and Le Dortz (2007) suggested the fault slips at 2 mm.yr⁻¹. This initial estimate has been further investigated by dating of optically stimulated luminescence (OSL) samples collected within colluviums thought to predate the incision of an abandoned fan. Nazari et al (2009) derived a minimum slip-rate of 0.8-2.5 mm.yr⁻¹ by combining the offset of two gullies incised within the fan with the weighted mean OSL age of the colluviums. However, neither the offset-gullies nor the surface of the abandoned fan have been dated directly. Nazari et al. (2009) collected primarily the OSL samples for paleoseismic purpose, within the fault zone where fanglomerate layers have been disrupted and/or warped.

In order to date the surface of the fan and provide further constraints on the slip-rate, we have sampled the surface to estimate its cosmic ray exposure (CRE) age and the sediments below the surface for OSL dating of their emplacement. While these two dating techniques are commonly used separately, a few recent studies have combined luminescence dating with cosmogenic data. In some cases the two methods yielded comparable ages though the CRE ages are always slightly older than the OSL ones (e.g. Owen et al., 2003, 2006; De Long and Arnold, 2007). Other studies yielded to significant differences, CRE ages being as much as twice older than the OSL ones (Hetzel et al., 2004; Nissen et al., 2009; Le Dortz et al., 2009). Some authors favoured the CRE ages whether they used surface samples only (Hetzel et al., 2004) or near-surface samples only (Nissen et al., 2009). Others (Le Dortz et al., 2009) that used both surface and near-surface samples concluded to a variable inheritance for the CRE ages and favoured the OSL ages for dating the abandonment of alluvial surfaces.

We performed the sampling at two sites on the southern portion of the fault where Meyer et al. (2006) documented right-lateral offsets of imbricate fan surfaces and riser cuts (Figure 1). To constrain the age of the abandoned fan surfaces and the age of the subsequent
incision, we collected 100 samples (73 surface samples and 27 near-surface samples along three profiles) to determine their CRE age by measuring the accumulation of $^{10}$Be and $^{36}$Cl cosmogenic nuclides. Using two isotopes with markedly different half-lives offered the opportunity to better constrain the erosion rate and evaluate the trade-off between erosion and CRE age of the studied surfaces. We also collected six additional samples within quartz-rich sandy layers located below alluvial surfaces to measure by OSL the time elapsed since the last sunlight exposure of the sediment.

First, we describe the detailed morphology of the two sites with emphasis on inset terrace levels imbricate within successive alluvial fan systems. Then, we present the results of the CRE and OSL dating and discuss how far they help constraining the abandonment age of the terrace treads and the age of the riser cuts that bound the treads. Finally, we discuss the slip-rate of the Dehshir fault and the morphoclimatic chronology of the area.

2. Offset Quaternary fans along the southern portion of the Dehshir fault

2.1 Site Dehshir South: Marvast River

The Marvast River is the largest and the most active of the intermittent rivers draining the study area, a dryland part of endorheic Central Iran Plateau. The river course is about 70 km long from its source within the High Zagros to the South of the Marvast city. The incision of the Marvast River is limited because it vanishes into the Marvast salt flat, whose base level stands at the elevation of 1520m. The drainage basin of the Marvast River is about 1100 km$^2$, and the upstream catchment drains several distinctive rock units including cover (Zagros platform lithologies) and basement (Sanandaj Sirjan metamorphics). The river and its former tributaries have emplaced the vast Quaternary piedmont made of coalescent fans that cover most of the surface on the satellite imagery of figure 1. The recent incision of the piedmont has resulted in a narrow channel supplying water to the city of Marvast, the formation of inset terraces, and the fan head entrenchment. The Dehshir fault cuts across the Marvast River, the active fans and the abandoned fan systems (Figure 2). To the west of Marvast city, several inset terraces are distinguished (T0, T1a, T1b, T2, T3) and their relative age can be assessed by their relative elevation (Figure 3). The material of each terrace, well layered, is of fluvial-torrential origin and contains polygenic cobbles (Figure 3). The lower terrace T0 corresponds to the present-day overflowing flood channel of the Marvast River. Many braided channels up to 0.5-0.8 m deep incise T0. Very loose conglomerates alternate with silty-sandy layers. The pebbles and the cobbles, either in the riverbed or on the surface of T0 are well rounded and have not experienced cryoclasty. T1 is a terrace located 1 to 3 m above T0. T1 is made of two
distinctive levels, T1b slightly older and 1 m above T1a. Both T1a and T1b levels have been
probably emplaced during the same climatic period. They contain pebbles and well-rounded
cobbles with diameters up to 30 cm. The material is poorly cemented and some sandy layers
are found intercalated within the slightly indurate conglomeratic layers. Cobbles on the T1
surface display bar and swell morphology, most of them are well rounded very few have been
fragmented suggesting a very limited cryoclasty. T2 is an older terrace standing about 4-5 m
above T1 upstream of the Dehshir fault and 2-4 m above the present streambed downstream.
Several indurate sandy layers alternate with coarse conglomerates. T2 surface is flat and many
fragmented cobbles are found on it, suggesting that the terrace underwent low temperatures
and contrasted seasons during long period of times associated with strong wind deflation, as
under glacial climates. The upper part of the terrace is fairly cemented by a discontinuous
calcrete up to 1 m thick at some places. T3 is the top surface of the highest alluvial fan
system. It stands more than 5 m above T2. Where exposed upstream, by the Marvast incision,
T3 contains many cryoclasted cobbles and a few large cobbles. The conglomerate levels are
strongly indurate and the upper part of T3 is cemented by a continuous, 0.4-0.8 m thick,
reddish calcrete. Numerous gelifracted cobbles can be found on its surface. Many gullies
incise T3; they are deeper and wider than the shallow immature rills incising T2. The overall
terrace has a characteristic striped-morphology on the satellite imagery with flat strips
separated by narrow intervening intermittent gullies (Figure 2).

There are also a few remnants of older fanglomerates cropping out close to the fault
(Figure 2). These older conglomerates are assigned to the Pliocene according to the geological
mapping by GSI (1981). The layers are mostly tilted to the west and squeezed within the fault
zone, but the orientation of the cobbles indicates an eastward paleocurrent direction (Meyer et
al., 2006). The successive fans have been all emplaced by the Marvast River and
progressively deformed through time. The most recent riser cut of the Marvast river stands
between T1 tread and the river course (T1b/T0) West of the fault and between T2 tread and
the river course (T2/T0) East of the fault. This T2/T0 riser, deflected in a right-lateral sense
by an amount of 25 ± 5 m, is not a passive marker and might have been rejuvenated by lateral
erosion (Figure 2a). Several larger offsets occur further to the South. About 2 km south of the
Marvast River, a large dry river, deeply incised within the oldest fan T3, is right-laterally
offset by 380 ± 20 m (Figure 2b). This offset is higher than the 180-200m offset streams
described by Meyer et al. (2006) a little further to the South. The latter offsets correspond to
streams that are narrower and less incised than for the former. Consequently, the value of 380
± 20 m corresponds to the largest dextral offset observed amongst the many rivers incising T3 and provides a minimum bound of the fault motion since the abandonment of T3 tread.

2.2 Site Dehshir North

The site Dehshir North is located about 25 km north of the Marvast River (Figure 1). The site lies close to a 30 km long, north-south trending, intermittent stream in which present-day drainage is mostly restricted to the northern part of the piedmont. The stream is disconnected from the Marvast River but it grades almost back to the Marvast River outlet from the Sanandaj Sirjan Mountains and drains a significant area of the Quaternary piedmont. At site Dehshir North, the piedmont mainly consists of the distal part of the abandoned fan T3 (Figure 4). Similarly to the site Dehshir South, several lower levels (T2, T1b, T1a) with limited extension are nested within the alluvial fan T3. The material of each terrace is also of fluvial-torrential origin but the gravel sizes are smaller than at site Dehshir South. Fine content is higher and the coarser levels are void of boulders.

The higher level T3, although much resembling that along the Marvast River on the SPOT Imagery, has been a little less incised and dissected by the rivers than at Dehshir South. At Dehshir North, T3 stands about 4 m only above the active riverbed (Figure 4b) and its surface displays many cryoclasted cobbles. T3 is incised upstream by many short gullies regularly spaced every 20-30 m. Such gullies probably formed as a result of regressive erosion after the abandonment of the terrace T3 and the cutting of the risers. T2 has a very limited extension with respect to T3. It is a lateral fan sloping down gently northward that was aggraded by small local tributaries that are incised within T3 terrace and rework its alluvial material. T2 surface stands 2-4 m below T3 and is much less incised than the old terrace; only a few short gullies irregularly spaced are distinguished on the Quickbird Imagery (Figure 4a).

As T3, the surface of T2 displays cryoclastic material. The emplacement of the lateral fan T2 is partly controlled by the local development of the Dehshir fault. The terrace T1 lies 1 m at most below the terrace T2 and stands 1 m above the riverbed T0. Most of the gullies that incise T3 and T2 merge downstream with T1 and their incision is probably synchronous with the emplacement of T1. The surface of T1 displays only very few cryoclasted cobbles.

Similarly to the site Dehshir South, two levels (T1a and T1b) can be distinguished, with T1b being older and standing 0.5-1 m above T1a. Both the terrace T1 and the lateral fan T2 are nested in the highest terrace T3 and have a very limited extent.

Some small gullies that incise T3 and T2 cross the fault zone at a right angle. Two of these gullies are clearly offset in a right-lateral sense by 20-30 m (figure 4), an amount similar
to the deflection of the Marvast River at the site Dehshir South. These gullies postdate the
emplacement of T3 and T2 and might have formed as a result of regressive erosion since the
last significant incision of the network. Their incision is probably coeval with the
emplacement of the terrace T1 with which they merge downstream, and the gullies, according
to weighted mean OSL dating in a trench within the fault zone, are supposed to be younger
than 21.1 ± 11.2 ka (Nazari et al., 2009). There is also an offset of the right bank of the main
river flood channel (Figure 5). Upstream, the most recent riser cut (T3/T0) stands between T3
tread and the riverbed. Downstream, T1 is protected from erosion because of the right-lateral
motion of the fault and the most recent riser stands between T1 tread and the riverbed
(T1a/T0). The riser that postdates the terrace T1a is offset by 12 ± 2 m (Figure 5).

3. Chronology of the regional fans

The dating of the alluvial surfaces and inset terraces at both sites is required to establish
the chronology of the fans and constrain the age of the offset-risers. Two complementary
dating methods, cosmic ray exposure (CRE) and optically stimulated luminescence (OSL),
have been performed to estimate the age of abandonment of alluvial surfaces. OSL relies on
natural background radioactivity of the material with a small contribution of cosmogenic
radiation and measures the time elapsed since the last sunlight exposure of a sediment layer.
CRE provides the time of exposure of superficial material to cosmic rays.

3.1 Sampling strategy and analytical procedures for cosmogenic and OSL dating

All the terraces (T0, T1, T2 and T3) were sampled at each site for cosmogenic dating.
For some surfaces (T3 at sites Dehshir North and Dehshir South, T2 at site Dehshir South)
and taking advantage of the occurrence of polygenic cobbles, both the $^{10}$Be and $^{36}$Cl
cosmogenic nuclides dating techniques have been applied. We measured the concentrations of
in-situ produced $^{10}$Be and $^{36}$Cl accumulated respectively in quartz-rich and carbonates samples
exposed to cosmic rays. Surface samples were collected to estimate the CRE ages (Table 1).
Most of the surface samples, 67 over the 73 collected, consists of individual cobbles, 4
correspond to two fragments of the same gelifracted cobble, and 2 only are amalgams of
many (about 25) pieces of small pebbles. Near-surface samples were also collected along
three profiles to estimate the inheritance, i.e., the concentrations of cosmogenic nuclides
accumulated in the cobbles prior to their deposition. Each near-surface sample is an amalgam
of pebbles or fragments of cobbles collected at the same depth. Provided that the sediment
emplaced in a short period of time and that the pre-exposure is homogeneous, the exponential
decrease of concentrations with depth provides an estimate of the homogeneous inheritance (e.g. Anderson et al., 1996; Repka et al., 1997). The inherited concentration is determined from the asymptotic value that the profile tends to at depth and a chi-square inversion is often used to minimise the differences between measured and modelled concentrations (e.g., Siame et al., 2004; Braucher et al., 2009). Collecting pebbles from the active streambed also helps to estimate the inherited component (e.g. Brown et al., 1998). However, this method relies on the questionable assumption that the pre-depositional history of the pebbles collected in the present-day streambed is comparable to that of the pebbles collected on abandoned fan surfaces during aggradation stages.

Three main types of secondary particles are involved in the in situ production of $^{10}\text{Be}$: fast nucleons (essentially neutrons), stopping (or negative) muons and fast muons. Each of them has its own effective attenuation length. We used in this paper the same parameters as Braucher et al. (2003) for the muonic attenuation lengths that are 1500 g.cm$^{-2}$ for stopping muons and 5300 g.cm$^{-2}$ for fast muons. For fast neutron, an attenuation length of 160 g.cm$^{-2}$ (Gosse and Phillips, 2001) is used rather than the attenuation length of 177 g.cm$^{-2}$ (Farber et al., 2008) modelled at mid-latitude in California but without accounting for the muonic contribution. Samples were prepared at the CEREGE laboratory in Aix-en-Provence for $^{10}\text{Be}$ concentration measurements following chemical procedures adapted from Brown et al. (1991) and Merchel and Herpers (1999). After addition in each sample of ~100 µl of an in-house $3.10^{-3}$ g/g $^{9}\text{Be}$ carrier solution prepared from deep-mined phenakite (Merchel et al., 2008), all $^{10}\text{Be}$ concentrations were normalized to $^{10}\text{Be}/^{9}\text{Be}$ SRM 4325 NIST standard with an assigned value of $(2.79 \pm 0.03).10^{-11}$. This standardization is equivalent to 07KNSTD within rounding error. All $^{10}\text{Be}$ data reported in this study (Table 1) have been measured at ASTER (CEREGE, Aix-en-Provence). Analytical uncertainties (reported as 1σ) include uncertainties associated with AMS counting statistics, AMS external error (0.5%), chemical blank measurement. Long term measurements of chemically processed blank yield ratios on the order of $(3.0 \pm 1.5).10^{-15}$ (Arnold et al., 2010). Cosmocalc add-in for excel (Vermeesch, 2007) has been used to calculate sample scaling and standard atmospheric pressures. Stone (2000) polynomial has been used to determine surficial production rate assuming a SLHL production rate of 4.49 at.g$^{-1}$.yr$^{-1}$ for $^{10}\text{Be}$.
$^{36}$Cl can be produced by two mechanisms in superficial rocks, cosmic ray interactions (spallation reactions of Ca, K, Ti and Fe, capture of low energy epithermal and thermal neutrons by $^{35}$Cl, and direct capture of slow negative muons by K and Ca) and radiogenic production by disintegration of U and Th. To determine the proportion of radiogenic $^{36}$Cl requires measuring the concentrations of U and Th in the target mineral (Zreda et al., 1991; Stone et al., 1996, 1998; Gosse & Phillips 2001; Schimmelpfennig et al., 2009). Major elemental compositions of rock samples were determined by ICP-OES technique by the CNRS service for rocks and minerals analysis at CRPG Nancy. For the $^{36}$Cl measurements, the chemical extraction of chlorine by precipitation of silver chloride has been adapted from the protocol of Stone et al. (1996). The samples were spiked with a known quantity of stable chlorine carrier (e.g. Desilets et al., 2006) to simultaneously determine $^{36}$Cl and chlorine concentrations by isotope dilution accelerator mass spectrometry (AMS). The chemical treatment of the samples was carried out at the CEREGE laboratory in Aix-en-Provence and the measurements were performed at the Lawrence Livermore National Laboratory, using KNSTD1600 standard. The excel spreadsheet provided by Schimmelpfennig et al., (2009) was used to calculate all $^{36}$Cl production rates and to model $^{36}$Cl data. Accordingly, a surface spallation rate of $48.8 \pm 3.4$ at.g$^{-1}$(Ca).yr$^{-1}$ (Stone et al. 1996) is used. However we use a neutron attenuation length of 160 g.cm$^{-2}$ (Gosse & Phillips 2001) instead of 177 g.cm$^{-2}$ (Farber et al., 2008) as explained above and for self consistency. The concentrations of in-situ produced $^{10}$Be and $^{36}$Cl are given in Table 1 and the chemical composition of the carbonate samples in Table 2.

Optically stimulated luminescence was used to date the alluvial layers emplaced during the aggradation of the fans. Lenses of fine sandy-silts intercalated between conglomerates at various depths below the surface were sampled for OSL in opaque tubes. The Single Aliquot Regeneration (SAR) protocol (e.g.; Murray and Wintle, 2000) was employed for the Equivalent dose (De) measurement once quartz had been extracted and cleaned from each sample. The analytical procedures employed are identical to that applied to similar samples from the neighbouring Anar, Sabzevar and Doruneh areas (Le Dortz et al., 2009; Fattahi et al, 2006; 2007).

Initial attempts to use single grains for De determination failed due to the dimness of OSL signal. As a result De measurements were undertaken on 9.6 mm diameter aliquots containing approximately 1500-2000 grains. Whilst normally this might result in averaging...
out of any multiple dose component within a sample, here it is assumed that for these dim
time samples the luminescence signal from each aliquot was produced by a relatively few number
of bright grains and thus may be considered as almost measuring at single grain level.
Therefore, the $D_E$ distribution of the single aliquot $D_E$ measurements is considered to be
almost a true reflection of the actual $D_E$ distribution within a sample. For some samples the
depositional setting, field sedimentary logs and the scatter of the replicate aliquot $D_E$ data
indicated that prior to burial, full resetting (bleaching) of the OSL signal had not taken place
and/or that the sediments had undergone some post-depositional disturbance (Bateman et al.,
2007). As a result of this, Finite Mixture Model (FMM; Roberts et al. 2000) was used where
samples showed skewed, scattered, or multimodal distributions. We used the dominant FMM
component for samples displaying multimodal $D_E$ distributions and the lowest FMM
component of $D_E$ for samples whose $D_E$ distributions were skewed (assuming partially
bleached without significant bioturbation) samples (Boulter et al., 2007; Bateman et al.,
2007). Where samples had a low over-dispersion and unimodal, normally distributed $D_E$’s
then the Central Age Model (CAM; Galbraith et al., 1999) $D_E$ was used for age calculation
purposes. The relevant information for OSL ages are presented in Table 3 in years from
present with 1 sigma errors.

3.2 Cosmic ray exposure ages

Figure 6 displays the results for the site Dehshir North, and figure 7 for the site Dehshir
South. The concentrations are given in Table 1 with the corresponding CRE ages modelled
assuming erosion and inheritance are negligible.

3.2.1 Surface T3

For T3, both the $^{10}$Be and $^{36}$Cl zero-erosion, zero-inheritance ages of surface samples are
overall consistent and suggest that the terrace tread is old.

At Dehshir North (Figure 6), the CRE ages range between 235 and 519 ka for the $^{10}$Be
measurements, and between 268 and 383 ka for the $^{36}$Cl measurements. For the $^{10}$Be
concentrations, all but one surface sample provide CRE ages greater than 400 ka. The younger
$^{10}$Be exposure age (DN06S2, 235.5 ± 35.4 ka) might be considered as an outlier and excluded
from the statistics. Then, the weighted mean of the zero-erosion zero-inheritance $^{10}$Be model
age of T3 is 462 ± 55 ka while the $^{36}$Cl one is 325 ± 74 ka (Figure 6b).
At site Dehshir South (Figure 7), the scattering of the concentrations is greater. The weighted means of the zero-erosion zero-inheritance $^{10}$Be and $^{36}$Cl ages are $481 \pm 119$ and $344 \pm 83$ ka, respectively (Figure 7b). The results are nonetheless similar at both sites and confirm the qualitative inference of the synchronism of levels T3 drawn from the resemblance of their surface at distant sites on the Quickbird imagery. They indicate T3 is a rather old surface (several hundreds ka) and that $^{36}$Cl surface ages are a little younger than $^{10}$Be ages. The slight difference between the $^{10}$Be and $^{36}$Cl weighted mean ages may either result from a statistical bias due to the limited number of samples or be meaningful. The $^{36}$Cl half-life (301 ka, e.g. Gosse & Philipps, 2001) being lower than that of $^{10}$Be (1.387 ± 0.12 Ma, Chmeleff et al., 2009; Korshinek et al., 2009) and T3 an old terrace, the difference may suggest the carbonates have reached the steady-state equilibrium for which the production of $^{36}$Cl is balanced by the loss due to radioactive decay and the loss due to erosion, if there is any.

Because there is a trade-off between denudation rate and exposure age, it is important to estimate the erosion. Assuming an infinite age for the emplacement of T3 allows estimating a maximum erosion rate for each of the surface samples, both for $^{36}$Cl and $^{10}$Be isotopes (Table 1). For the carbonates, none of the surface samples provides a $^{36}$Cl maximum denudation rate greater than 2.1 m.Ma$^{-1}$, and the averaged value is 1.5 m.Ma$^{-1}$. Discarding the outlier DN06S2, the quartz surface samples indicate a $^{10}$Be maximum denudation rate smaller than 1.6 m.Ma$^{-1}$ with an averaged value of 1.4 m.Ma$^{-1}$. This is further strengthened by modelling the depth-distribution of the $^{36}$Cl concentrations in the amalgamated carbonate samples collected along a 3 m depth profile excavated in T3 at the site Dehshir North (Figure 8). The profile shows an overall exponential decrease of concentrations with depth allowing for modelling the erosion rate. The $^{36}$Cl concentration depth profile is modelled with assigning a surface age of 3 Ma; old enough to ascertain the equilibrium between production and disintegration has been reached. Letting the erosion rate and the inheritance free to vary, the profile is modelled for three density values (between 2 and 2.4 g.cm$^{-3}$) within the range of that measured for the samples of the profile (Figure 8). For all the densities tested, the model converges towards zero inheritance solutions and low erosion rates. The solutions with zero inheritance are not surprising because the assigned surface age of 3 Ma makes a homogeneous inheritance of several tens of ka undetectable. By contrast, the solutions with low maximum erosion rates are meaningful. The greatest erosion rate of 1.90 m.Ma$^{-1}$ is obtained for a density value of 2 g.cm$^{-3}$. Smaller erosion rates of 1.48 and 1.18 m.Ma$^{-1}$ corresponding to densities of 2.2 and 2.4
g.cm\(^{-3}\) are closer to the erosion rate calculated for each of the carbonate surface samples (Table 1).

Whatever the method applied (surface sample, near-surface samples and depth-profile modelling) and whatever the isotope considered, the estimates of the maximum erosion rate are very low. They are close to that found in hyperarid regions (<1 m.Ma\(^{-1}\), Matmon et al., 2009) and in good agreement with the pristine morphology of the flat-topped surface of T3. The \(^{10}\)Be depth profile can be theoretically modelled with erosion rates ranging between 0 and 1.4 m.Ma\(^{-1}\), maximum erosion rate averaged from the \(^{10}\)Be surface samples. Accounting for the trade-off between erosion rate and exposure age (the higher the erosion rate, the older the exposure age), the \(^{10}\)Be depth profile has been modelled under the assumption of no erosion to minimize the exposure age. We hence tested a range of inheritance values to solve for the zero erosion exposure age (Figure 9). The best fit is obtained for a surface age of 464 ka and a homogeneous inheritance of 3.8 \(10^5\) at.g\(^{-1}\)(SiO\(_2\)). This inheritance, if acquired at the surface and prior to the emplacement of the terrace, would correspond to a period of pre exposure of about 32 ka, small with respect to the exposure age. Accounting for the trade-off between inheritance and age, several other solutions remain acceptable (Figure 9b). Assuming a homogeneous inherited concentration of 7.6 \(10^5\) at.g\(^{-1}\)(SiO\(_2\)), twice that obtained for the best fit and close to the concentration measured for the deepest sample of the profile, provides an age of 327 ka. Hypothesizing zero inheritance yields an older age of 686 ka that does not match with the concentrations of surface samples, demonstrating the usefulness of combining both surface and near-surface sampling.

In summary, T3 is a rather old and well-preserved alluvial surface, in which cobbles have incorporated a poorly constrained inheritance of several tens of ka. This amount of inheritance, though limited with respect to the CRE age of T3, contributes to the 469 ± 88 ka weighted mean age of all the quartz cobbles collected on the terrace tread at sites Dehshir North and Dehshir South (Figure 10).

3.2.2 Surface T2

At Dehshir North, only one amalgam quartz-rich surface sample has been dated on T2 fan surface. The zero-erosion zero-inheritance CRE age is 406.5 ± 26.5 ka (Table 1, Figure 6a). This age is a little younger than of the weighted mean age of T3 and agrees with the assumption that T2 aggradation at this site results from reworking of T3 material. Indeed, T2 CRE age is older than several ages that have been used to estimate the weighted mean age of T3 and much older than that of the T3 outlier. At Dehshir South, twelve samples collected on
T2 have been analysed (Figure 2a and Figure 7). The $^{10}$Be and $^{36}$Cl concentrations, hence the corresponding CRE ages calculated assuming zero-erosion and zero-inheritance are scattered (Table 1, Figure 7a). The CRE ages of the surface samples range between 49.9 ± 3.3 and 225.8 ± 14.7 ka for the $^{10}$Be and between 104.4 ± 10.5 and 190.3 ± 20.8 ka for the $^{36}$Cl. The youngest $^{10}$Be CRE age on T2 (DS08S114, 49.9 ± 3.3 ka) might be considered as an outlier and excluded from the statistics. Discarding the outlier and keeping in mind the limited number of samples, the ages remain scattered without significant differences between $^{10}$Be and $^{36}$Cl ages. The distribution is multimodal with a weighted mean CRE age of 175 ± 62 ka (Figure 11a). This average is consistent with the intermediate elevation of T2 terrace and its surface characteristics as well as the fact that none of the CRE ages obtained for T2 is older than the youngest age calculated for T3.

Amalgamated samples have also been collected along two depth profiles at site Dehshir South. The $^{10}$Be concentrations are listed in Table 1. The profile PS1 was collected by the riser between T2 and the Marvast riverbed, 300 meters East of the fault zone (Figures 2 and 11). The profile PS2 has been collected 1.5 kilometres NE of PS1, close to the fault scarp in a pit dug within the T2 surface and nearby remnants of T3 (Figures 2 and 12). For both profiles, the uneven distribution of the $^{10}$Be concentrations dismisses a uniform pre-exposure prior to the emplacement of T2 material and precludes any appropriate modelling of a homogeneous inheritance. As for the study of alluvial surfaces in the Anar neighbouring area (Le Dortz et al., 2009), the profile data, together with the scattering of the concentrations of the surface cobbles, suggest the occurrence of a variable inheritance.

3.2.3 Surface T1 and T0

At site Dehshir North, the four surface samples collected on T1a provide CRE ages ranging between 82 and 424 ka (Figures 4 and 6a). The sample with the oldest age might be considered an outlier and the CRE age of the terrace would be better determined by the three youngest samples and bracketed between 82 and 134 ka. The T1a outlier has an age close to that of the amalgam on T2 fan surface and close to that of the surface samples collected on T3. This suggests that the T1a outlier is a T2 or T3 cobble reworked by the small gullies incising the surface of T2 and T3 treads and which incision is coeval with the emplacement of T1.

At site Dehshir South, the four surface samples have been collected on T1b. They provide $^{10}$Be exposure ages ranging between 30 and 318 ka (Figures 2 and 7a). The oldest sample, even older than the samples collected on T2 tread, is as an outlier. Either it is a
former cobble of T3 locally reworked by the small gullies incising T3 or a cobble exposed to cosmic rays for a long time in the upstream catchment of the Marvast River. In any case, such an outlier indicates that the inheritance of individual cobbles collected on T1 tread can be very important. Off the three remaining samples collected on T1b, two provide CRE ages that are not distinguishable from the CRE weighted mean age (175 ± 62 ka) of T2, the terrace immediately above. Only one sample (DS08S124, 32.1 ± 2.1 ka) provides an age significantly younger than the ages on T2. This CRE age on T1b surface is significantly younger than the CRE ages on the T1a surface at site Dehshir North, suggesting that at this latter location, the surface cobbles of the T1a terrace contain an important amount of inherited $^{10}$Be.

At site Dehshir South, five samples have been collected in the present day streambed of the Marvast River. Whatever the isotope considered, all provide non-zero CRE ages ranging between 54 and 96 ka, suggesting the occurrence of a significant inheritance. The CRE ages of T0 are younger than the CRE ages of T1b except for the youngest sample of T1b (DS08S124, 32.1 ± 2.1 ka). At site Dehshir North, four samples have been collected in the main river flood plain T0. Discarding the outlier, three samples (two $^{10}$Be ages and one $^{36}$Cl age) provide non-zero CRE ages ranging between 57 and 84 ka, confirming the occurrence of a significant inheritance averaging some 70 ka. When including the outlier corresponding to the oldest sample collected in the river, the scattering of the concentrations increases and suggests the pre exposure history of a cobble before the abandonment of an alluvial surface is highly variable.

To summarize (Figure 13a), the observed average inheritance in the present stream beds of some 70 ka, as well as the distribution of CRE ages for the inset levels T1 and T2, suggest that T1 and T2 treads are likely to be younger than their CRE weighted mean age. Thus, the ages of abandonment of the terrace treads may be better approximated by the CRE age of the youngest sample found on each surface. Such a conclusion has already been drawn for alluvial fan surfaces in the neighbouring region of Anar (Le Dortz et al., 2009).

### 3.3 Optically stimulated luminescence ages

OSL dating was performed to better constrain the chronology of alluvial terraces at the two studied sites. Five OSL samples initially sought to determine the ages of faulted deposits for paleoseismology purposes were sampled at site Dehshir North (Nazari et al., 2009). Then, six new OSL samples were collected at site Dehshir South. As no suitable material was found within old terrace T3, OSL ages help only constraining the aggradation timing of terraces T2
and T1; they also permit comparison with CRE ages. The ages of all the OSL samples, including those previously published by Nazari et al. (2009), have been recalculated in section 3.1 using CAM or FMM techniques to account for the scatter of the De distributions.

OSL samples were collected at site Dehshir North, in a trench excavated within T3 and T2 (Figure 4 in Nazari et al., 2009). Within this trench, the distal alluvial and colluvial deposits corresponding to the T2 and subsequent levels provide refined OSL ages of 60.0 ± 5.7 ka, 45.5 ± 4.6 ka, and 20.1 ± 1.6 in accord with the stratigraphic succession (Table 3, sample HI/2008-IX in unit E1, sample HI/2008-VII in unit D3b, sample HI/2008-VIII in unit D4, Nazari et al., 2009). In addition, recent colluviums incised by small streams flowing through the Dehshir fault zone and which base level matches with the tread of T1 yielded two OSL ages of 26.0 ± 1.0 ka for the lower colluviums and 20.2 ± 0.8 for the upper ones (Table 3, sample HI/2008-I in unit B1 and sample HI/2008-VI in unit B2, Fattahi et al., 2010). These two latter OSL ages, which postdate the incision of T2, are coeval with the emplacement of T1. They imply that the T1b tread, all the more the T1a tread, is at most 21 ka (oldest possible age of the most superficial sample). Notwithstanding that the OSL samples have not been directly collected under the terrace treads sampled for CRE dating, the data available at site Dehshir North indicate large discrepancies between the CRE and OSL ages. The cannibalism of the old T3 terrace by subsequent alluvial deposits may explain such discrepancies by locally recycling T3 cobbles during the aggradation of the lower terraces T2 and T1. This possibility is further examined at site Dehshir South for which OSL samples have been taken right below the terrace treads T2 and T1 where sampled for CRE dating.

For T2 at Dehshir South, two OSL samples, OSL I and OSL II, have been collected from the riser between T2 and the active riverbed, very close to the profile PS1 (Figure 2a and 11b). OSL I has been collected 15 m to the West of PS1 and at a depth of 0.8 (OSL I) and OSL II, 10 m to the East of PS1 and at a depth of 3.4 m. The samples OSL I and II yielded ages of 26.9 ± 1.3 ka and 29.4 ± 5.1 ka, respectively (Table 3). These similar OSL ages suggest that the material of the terrace T2 emplaced rapidly and that its tread is at most 28.2 ka. The OSL samples of the riser T2/T0 provide ages much younger than the weighted mean ^10Be and ^36Cl CRE age of T2, 175 ± 62 ka (Figure 11a), but closer to 49.9 ± 3.3 ka, the youngest CRE age on T2 tread (DS08S114 in Table 1). Two additional OSL samples (AB/2006-I and II in Table 3) were collected within a colluvium pediment topping T2 in the pit of profile PS2 (Figure 2a and 12b). These samples yielded OSL ages of 39.7 ± 2.6 and 20.0 ± 1.3 which confirm this desert pediment was formed both by the end of the emplacement of terrace T2 and after its abandonment. To summarize, the OSL ages obtained
for T2 indicate its aggradation occurred during the time-interval 25.6-65.7 ka. This suggest
that the samples collected on T2 tread, providing exposure ages older than 66 ka, contain an
inherited CRE component, For T1, two OSL samples, OSL III and IV, were collected at
Dehshir South in fine sands respectively below the surface of T1b and T1a (Figure 3b). The
error bars on sample OSL III, taken by the riser T1b/T0, provide minimum and maximum
OSL ages of 20.4 ka and 23.4 ka for the T1b tread. The sample OSL IV, taken by the riser
T1a/T0, provides minimum and maximum OSL ages of 9.4 ka and 10.6 ka for the T1a tread.
These ages are in agreement with the relative elevation of the terraces, the samples from the
riser T2/T0 being older than the sample from the riser T1b/T0, itself older than the sample
from the riser T1a/T0. Similarly to the terrace T2, the OSL age of T1b is younger than the
$^{10}$Be CRE ages of the samples collected on the T1b tread. This OSL age is almost one order of
magnitude younger than the three oldest $^{10}$Be samples and 30% younger than the youngest
$^{10}$Be sample (DS08S114). There is no direct comparison available between OSL and CRE
ages for T1a because this surface has not been sampled for cosmogenic dating.

At the two studied sites along the Dehshir fault, the OSL ages on terraces T2 and T1
are systematically younger than the CRE ones on the same terrace. For a given terrace, the
CRE statistical outlier, which is the youngest CRE age and has been consequently removed
from the calculation of the weighted mean CRE age, remains slightly older than, but closer to
the OSL ages. Two extreme options may be contemplated: either OSL ages have been
rejuvenated or CRE concentrations include a high percentage of inheritance. Most of the
physical processes that are known to affect the OSL method, such as partial bleaching,
incorporate an antecedent signal leading to overestimation of the age of sediment burial. This
has been accounted for the studied samples by the statistical processing of the De
distributions. Conversely, OSL signal is sensitive to the temperature and a loss of
luminescence might occur at temperatures above 50°- 60°C. Such temperatures may occur on
the Iran plateau during summertime so that OSL ages could be theoretically rejuvenated.
Nevertheless, to account for gamma rays shielding, OSL samples were taken at least at 0.7 m
below the ground surface (Table 3), a depth large enough to prevent strong variations of
temperature. In addition, if temperature had affected the OSL signal, such effect would
decrease with increasing sampling depth. However, no trade-off is observed between the OSL
ages and the sampling depth (Table 3). On the contrary, OSL ages, whatever the depth, appear
similar for the same terrace and in agreement with the relative elevation of the terraces. As a
consequence, the variable inheritance of CRE concentrations should chiefly explain the
discrepancy with OSL ages.
3.4 Discussion on the abandonment age of the alluvial surfaces

The overall chronology of the fan surfaces crossed by the Dehshir fault has been established but the abandonment age of each surface is not easily assigned for several reasons (Figure 13). First, the scattering of CRE concentrations on a given surface, the occurrence of more concentrated samples on younger surfaces than on older ones, the occurrence of significant concentrations in active river beds, indicate there is a variable inheritance uneasy to account for. Second, where CRE and OSL data are available for the same terrace, the OSL ages of the late sediments of the terrace are always much younger than the CRE ages of the cobbles abandoned on its tread. Such disparities between OSL and CRE ages appear to result from the high variability of the CRE inheritance that needs further consideration.

3.4.1 Variable CRE inheritance and maximum abandonment ages of alluvial treads.

A rough estimate of the variable inheritance is provided by the CRE weighted mean of 72 ± 20 ka obtained from 8 of the 9 samples collected in the riverbeds once the oldest outlier discarded. Moreover, amalgam sample DS08P130 from profile PS1 (Figure 11c) has a measured concentration (Table 1) of 8.66 10^5 at.g^-1(SiO_2), even though it is located at 2.1 m below the T2 surface whose surface samples yielded a weighted mean CRE age of 175 ± 62 ka. Assuming 175 ka represents the actual age of T2 tread and subtracting the concentration acquired in situ, at 2.1 m depth, by sample DS08P130 during these 175 ka of exposure would yield to a remaining, hence inherited, concentration of 7.25 10^5 at.g^-1(SiO_2). Most of the sample concentration would therefore result from inheritance. Such inherited concentration would have been acquired in about 60 ka, if accumulated at the surface. Then, the 70 ka ages of riverbed samples appear to give a good estimate of the amount of inheritance carried by T2 material. Consequently, T2 mean age should be reduced to 105 ± 62 ka. These 70 ka inheritance estimates are larger than the 32 ka of inheritance age-equivalent obtained for T3 by conventional modelling of the ^10Be profile (Figure 9). We have therefore investigated another method to use the inheritance. Assuming each terrace formed during a short-lived aggradation coeval with a single climatic crisis, the near-surface concentrations have been used to fix the maximum abandonment age of the terrace (Figure 14). The principle is simple and rests on the impossibility for any sample to be incorporated into the sediment of the terrace with a negative concentration. Accounting for the depth of each near-surface sample and assuming its measured concentration results only from in-situ
exposure; i.e. assuming no inheritance for the sample, it is possible to calculate for any
sample of a profile the time required to bring it back from its measured concentration to a null
concentration. The maximum abandonment age of the terrace is then obtained from the near-
surface sample of a given profile for which the concentration is restored to zero without
bringing back any other sample of the profile to a negative concentration. For the profile PS1
across T2 (Figure 14a), this is obtained for the sample DS08P127 with 107 ka of in-situ
exposure. This indicates that T2 was abandoned at most 107 ka ago and that for this
maximum time of exposure the concentration remaining in the other samples of the profile
correspond to a minimum inheritance. Therefore, this method figures out the variability of the
inheritance that amounts, for such an exposure time, to \(7.86 \times 10^5 \text{ at.g}^{-1} (\text{SiO}_2)\) for the near-
surface amalgam collected at 2.1 m depth; such concentration would correspond to a
minimum exposure of 66 ka if acquired at the surface prior to the emplacement of the terrace
(Figure 14a). It is worth noticing that this rejuvenation would bring back only one of the
surface samples to a negative concentration. This remains acceptable, as this sample is the
statistical outlier DS08S114. All the other such 107 ka-rejuvenated surface samples would
keep positive concentrations. While older depth-profile determined CRE ages of T2 are not
possible because they would bring, at least one of the near-surface amalgams, the amalgam
127 (Figure 14a), back to a negative concentration, younger exposure ages remain possible.
Theoretically, all exposure ages ranging between 0 and 107 ka are possible. On the one hand,
exposure ages ranging between 53 ka (oldest possible age of the youngest sample, DS08S114,
on T2) and 107 ka would make that statistical outlier younger than the age of the terrace. On
the other hand, exposure ages ranging between zero and 53 ka would be compatible with the
occurrence of the statistical outlier as well as the other surface samples collected on T2.

The same method applied to the depth profile PN across T3 (Figure 14b) demonstrates
the terrace was abandoned at most 412 ka ago, confirms the occurrence of a significant
inheritance which minimum amounts to 68 ka for the deepest amalgam collected at more than
3m depth, and exemplifies its variability. It is nonetheless important to notice that this is an
uppermost bound of exposure duration. This leaves open all the possibilities ranging between
the time of abandonment of T2 and 412 ka, hence at least the possibilities between 107 and
412 ka.

3.4.2 Abandonment age of terrace treads.

The age of abandonment of the uppermost level T3 is to be discussed with the only
data available, the CRE ages (Figures 13 and 15). One may rest on the statistical analysis of
the surface samples and retains the weighted mean age of 469 ± 88 ka. To account for the
inheritance incorporated in the former estimate, it is possible to subtract to that weighted
mean age the 32 ka of inheritance age-equivalent obtained from the modelling of the $^{10}$Be
profile. It is nonetheless worth noticing that this average inheritance has been modelled under
the incorrect assumption that the inheritance is homogeneous. Accounting for the variability
of the inheritance, the near-surface profile data are incompatible with an age older than 412 ka
(Figure 14b) and the large uncertainties of the former estimate (437 ± 88 ka) can be reduced
to the interval 349-412 ka (Figure 15). Alternatively, retaining the youngest sample and
allowing for the occurrence of a greater amount of inheritance would provide a much younger
abandonment age of 271 ka (oldest possible CRE age of the youngest sample). As there is
ample evidence for a large variability of the inheritance on the younger surfaces, one cannot
rule out the later hypothesis and may consider an age of 271 ka for the abandonment of T3.

The age of abandonment of the intermediate level T2 is easier to estimate because both
OSL and CRE ages are available. The weighted mean of the zero-erosion CRE age (175 ± 62
ka) is of little use for constraining the age of abandonment because of the variable inheritance.
Subtracting a possible inheritance of 70 ka (Figure 14a), a value similar to the average
obtained for the cobbles collected in the active riverbed, takes back the former estimate to 105
± 62 ka. Although limiting the uncertainties to the range 43 -107 ka, the upper bound on the
abandonment age (Figure 14a) allows for a wide range of possibilities, including the oldest
possible CRE age (53 ka) of the youngest surface cobble. Accounting for the occurrence of a
variable inheritance, this latter solution is a better estimate of the maximum age of
abandonment of the surface although the youngest cobble may also bear an inherited
component. This inherited component may correspond to the difference with the oldest
possible age of the youngest OSL collected below the tread of T2. The surface of T2 is
younger than the oldest possible age of the superficial OSL sample and is at most 28.2 ka at
site Dehshir South (Figure 13b). Assuming this OSL age is close to the actual abandonment
age of T2 tread, a forward modelling of near-surface concentrations of PS1 profile (fig 11c)
can be calculated with zero erosion and different choices of inheritance. Whatever the
selected value of homogeneous inheritance, none permits to account correctly for the uneven
distribution with depth of the measured near-surface concentrations. Nevertheless, two
limiting curves appear to bracket these measured concentrations, they correspond to 3.5 $10^5$
and 9 $10^5$ at.g$^{-1}$(SiO$_2$) of homogeneous inheritances (figure 11c). These values of inherited
concentrations would correspond to pre-exposure, if acquired at the surface prior to the
emplacement of the terrace, of 30 ka and 75 ka, respectively. Although these values of
inherited concentrations result from forward modelling based on the assumption that the
inheritance is homogeneous, they indicate the inheritances carried by the amalgam samples of
T2 sediments may be nearly as high as $10^6$ at.g$^{-1}$(SiO$_2$). It is worth noticing that all but one
measured surface samples have $^{10}$Be concentrations that are higher than $10^6$ at.g$^{-1}$(SiO$_2$).
Interestingly, subtracting to the near-surface samples the concentrations corresponding to 30
ka of in-situ exposure makes the residual concentrations, which correspond to inheritance,
noteworthy. This inherited concentration amounts to $8.57\ 10^5$ at.g$^{-1}$(SiO$_2$) for sample
DS08P130 at 2.1 m depth and corresponds to pre-exposure time at the surface of 71 ka. Thus
considering 70 ka of inheritance for T2 gravels is a reasonable estimate that can be proposed
to average the variable inheritance.

Finally, the OSL ages of the risers T1b/T0 and T1a/T0 indicates their respective tread
are at most 23.4 ka and 10.6 ka, respectively. Given the uncertainties associated to the OSL
ages of the risers and considering that partial bleaching has been accounted, the youngest
possible ages of T2, T1b, and T1a treads are respectively 25.6 ka, 20.4 ka, and 9.4 ka.

4. Slip-rate estimate and conclusions

The former chronology and offset-risers provide estimates on the minimum and
maximum slip-rate of the Dehshir fault. At site Dehshir South, the river course displaced by
380 ± 20 m is incised within the terrace T3. Combining the offset of 380 ± 20 m with the
maximum exposure age of 412 ka yields a minimum slip-rate of $0.92 \pm 0.05$ mm.yr$^{-1}$.
Assuming that the regional level T3 is coeval at both sites and that the oldest possible age of
the youngest sample collected on T3 (i.e., 271 ka) may approximate its abandonment, the slip-
rate would be at least $1.40 \pm 0.08$ mm.yr$^{-1}$. The 25m-deflection of the Marvast River might
also be used to estimate the slip-rate on a shorter period of time, but this deflection probably
overestimates the true tectonic offset because T1 tread is no longer observed downstream. The
offset of the gullies incising both T3 and T2 treads at site Dehshir North is a true tectonic
offset. This 20-30m offset provides reliable estimates of the upper and lower bounds of the
slip-rate. The offset cannot be older than the OSL age collected below the tread of T2 (OSL1
26.9 ± 1.3 ka) and accounts for a minimum slip-rate greater than 0.71 mm.yr$^{-1}$ (20 m in the
last 28.2 ka). The offset cannot be younger than the infilling of T1b and allows determining
the upper and lower bounds of the maximum slip-rate. The infilling of T1b being younger
than 21.9 ± 1.5 ka, the lower and upper bounds of the maximum slip-rate are respectively 0.85
mm.yr$^{-1}$ (20 m in the last 23.4 ka) and 1.47 mm.yr$^{-1}$ (30 m in the last 20.4 ka). The $12 \pm 2$m-
offset of the riser T1a/T0 at Dehshir North is also an estimate of the actual tectonic offset postdating the emplacement of T1a, which is at most 10.6 ka according to sample OSL IV (Table 3, Figure 13). The $12 \pm 2\text{m}$-offset yields a lower bound of the minimum slip-rate of $1.13 \pm 0.2 \text{mm.yr}^{-1}$. The early estimate of Nazari et al. (2009) can therefore be refined and the actual slip rate ranges between $0.93 \text{mm.yr}^{-1}$, largest of the conservative estimates of the minimum slip rate, and $1.47 \text{mm.yr}^{-1}$, safe estimate of the maximum slip rate. Therefore, the slip-rate of the Dehshir fault is well determined at $1.2 \pm 0.3 \text{mm.yr}^{-1}$ (Figure 15).

This study demonstrates the usefulness of combining CRE and OSL data to unravel the abandonment ages of alluvial fans and inset terraces in the desert environment of Central Iran. On the one hand, the use of $^{10}\text{Be}$ and $^{36}\text{Cl}$ cosmogenic isotopes with different half-lives allows constraining a very low denudation-rate of $0.001 \text{mm.yr}^{-1}$ for the terrace treads and alluvial fan surfaces of Central Iran. On the other hand, the combination of surface and near-surface sampling exemplifies the occurrence and the variability of inheritance in the cosmogenic isotope concentrations and emphasizes the difficulty in assessing abandonment ages of young alluvial surfaces with CRE measurements in such arid environment (e.g., Le Dortz et al., 2009). The scattering of the CRE surface and near-surface concentrations indicates that the cobbles have not been uniformly exposed to cosmic rays prior to their emplacement. This variable inheritance may originate from a differential exhumation and weathering of the bedrock catchments, or more likely for Dehshir sites, from reworking of cobbles originating from different levels of upper, hence older, fans. The abandonment age of an alluvial surface is thus better estimated by the CRE age of the youngest surface sample than by the weighted mean CRE age of many samples, as already formulated in Mongolia (Vassalo et al., 2007) and along the southern rim of the Tarim basin (Mériaux et al., 2005). However, the youngest sample on a surface may also incorporate inheritance and still overestimate the abandonment age. The amount of CRE inheritance potentially remaining in the youngest sample of a given surface may be obtained by comparing with the OSL age of the late sediments aggraded before the abandonment of the surface. For alluvial surfaces that are young with respect to the considerable amount of inheritance, up to 70 ka in the desert environment of Central Iran, the upper bound on the abandonment age of an alluvial surface appears best estimated by the OSL dating of the late sediment aggraded. For such young surfaces, the CRE measurements are complementary of OSL dating and can be used to unravel the complex history of weathering and transport in the catchment of desert alluvial
fans. Finally, such variable CRE inheritance, typifying arid endorheic regions without incision rates, may require more consideration than hitherto drawn for the Andes and Tibet plateaus.

Acknowledgments.

This study would have been impossible without financial assistance from INSU-CNRS (PNTS and 3F programs) and CNES-SPOT Image (ISIS program contracts ISIS0403-622 and ISIS0510-812). Université Pierre et Marie Curie (UPMC) and Geological survey of Iran (GSI) provided complementary funding and logistic assistance. KL received a Ministry of Research and Education scholarship granted by the President of UPMC. The $^{10}$Be measurements were performed at the ASTER AMS national facility (CEREGE, Aix en Provence) that is supported by the INSU/CNRS, the French Ministry of Research and Higher Education, IRD and CEA. The $^{36}$Cl measurements were performed at the LLNL-CAMS. We thank L. Leanni, K. Pou, B. Finkel, F. Chauvet, M. Arnold and G. Aumaître for their help during chemistry and measurements at CEREGE and acknowledge B. Oveisi and M. Nazemzadeh for efficient organization and help during fieldwork. We acknowledge thorough reviews by Richard Walker and Anne-Sophie Mériaux. We are very thankful to Anne-Sophie Mériaux for her acute verification of the cosmogenic calculations.

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**Figures captions**

**Figure 1:** Spot imagery of the southern part of the Dehshir fault, near Marvast town. The fault cuts across abandoned alluvial fan systems and active rivers. Boxes indicate locations of Figures 2 and 4. The inset is a Landsat mosaic of the Dehshir fault and surroundings. The Nain Baft ophiolite outcrops are stylized in purple. The total dextral offset of the fault (65 ± 15 km) is outlined by the displacement of the suture.

**Figure 2:** Site Dehshir South. a) Quickbird imagery. The fault trace cuts across the Marvast River, intermittent channels and successive abandoned fans and terraces (T3 in orange, T2 in yellow, T1 a and b in green). The numbered dots show the position of the surface samples collected for $^{10}$Be and $^{36}$Cl CRE dating (red and blue dots, respectively). The black squares show the position of the near-surface samples collected along depth profiles PS1 and PS2 (Figure 11, 12 and 13). The black dots locate the OSL samples taken below the ground surface. AB locates the topographic profile of figure 3. b) Close up on the 380 ± 20m dextral offset of a river course, incised within the oldest (T3) fan surface.

**Figure 3:** a) Topographic profile across the abandoned fan system (see location on figure 2) highlights the relative elevation of the terraces and their degree of incision by the Marvast river. The profile is work out from a differential GPS survey. b) Field photograph of the inset terraces. Location of OSL III and IV are indicated on the close up pictures of the risers T1b/T0 and T1a/T0 respectively.

**Figure 4:** Site Dehshir North. a) Quickbird imagery. Different coloured shading denotes the successive abandoned fans (same code as for Figure 2). Numbered dots show the position of the surface samples collected for $^{10}$Be and $^{36}$Cl CRE dating (red and blue dots, respectively). The black square shows the position of the near-surface samples collected along the depth profiles PN (Figure 7 and 8). The black dots locate the OSL samples taken below the ground surface. Rectangle denotes the close up on the offset riser on figure 5. Dotted circles indicate location of 20-30 m right-lateral offset-gullies. Black (AB and CD) and white (RI) lines locate topographic sections on each side of the fault and on the riverbed respectively. b) Topographic profiles, achieved from differential GPS survey and projected along fault strike, highlight the amount of stream incision upstream and down stream of the fault. The offset-gullies are indicated.
Figure 5: a) Raw (left panel) and interpreted (right panel) images of the dextral offset of the recent riser (T1a/T0). Open triangles point to the fault trace and arrows to the foot of the riser. Rectangle denotes the enlargement on the offset-riser b) Quickbird image wrapped on the digital elevation model worked out from a DGPS survey. c) Enlargement on the 12 ± 2 m offset-riser (T1a/T0 downstream, T3/T0 upstream). The blue line denotes the base of the riser. d) Field photograph of the offset-riser with vertical arrows pointing to the foot of the riser.

Figure 6: Summary of observations at site Dehshir North. a) \(^{10}\)Be and \(^{36}\)Cl CRE ages of surface samples modelled without erosion and without inheritance are indicated by red and blue dots above each surface. The shaded columns extend from the minimum age to the maximum age given by the error bars of the samples. The OSL samples collected beneath each surface are indicated in stratigraphic order (see text for discussion). The plot of CRE ages is given for each surface sample, in relative position from north to south. Dots and errors bars are in red and blue for \(^{10}\)Be and \(^{36}\)Cl, respectively. b) Distribution of in-situ produced \(^{10}\)Be (left panel) and \(^{36}\)Cl (right panel) CRE ages modelled without erosion and without inheritance for the surface samples collected on T3 tread. The thin curves represent the CRE age probability as Gaussian distribution for each individual sample and the thick curves correspond to the summed Gaussian density probability function. The weighted mean CRE age is obtained with errors equal to two standard deviations (2 \(\sigma\)). Outlier sample DN06S2 (235.5 ± 35.4 ka) has not been included in the \(^{10}\)Be statistics.

Figure 7: Summary of observations at site Dehshir South. a) \(^{10}\)Be and \(^{36}\)Cl CRE ages of surface samples modelled without erosion and without inheritance are indicated by red and blue dots above each surface. The shaded columns extend from the minimum age to the maximum age given by the error bars of the samples. The OSL samples collected beneath each surface are indicated in stratigraphic order (see text for discussion). The plot of CRE ages is given for each surface sample, in relative position from north to south. Dots and errors bars are in red and blue for \(^{10}\)Be and \(^{36}\)Cl, respectively. b) Distribution of in situ produced \(^{10}\)Be (left) and \(^{36}\)Cl (right) CRE ages modelled without erosion and without inheritance for the surface samples collected on T3 Tread. The thin curves represent the CRE age probability as Gaussian distribution for each individual sample and the thick curves correspond to the
summed Gaussian density probability function. The weighted mean age is obtained with errors equal to two standard deviations (2 $\sigma$).

Figure 8: Plot of the near-surface, measured $^{36}$Cl concentrations (black dots) as a function of depth at profile PN (location on figure 4). Surface samples (blue dots) are shown but not included in the modelling. The erosion rate is modelled for a 3 Ma-old surface to ensure that the steady state equilibrium between production and disintegration has been reached. For the three different densities tested (obtained from the near-surface samples), the best-fit erosion rate – inheritance is indicated.

Figure 9. a) Plot of the near-surface, measured $^{10}$Be concentrations (black dots) as a function of depth at profile PN (location on figure 4). Surface samples are indicated as red dots. The modelled curves fit distributions of concentrations, without erosion, and for three assigned inheritances. The modelling includes both the near-surface samples and the weighted mean age of the surface samples (DN06S2 excluded). b) Log ($\chi^2$) values for a range of inheritance and CRE ages modelled without erosion are plotted below. The modelling converges towards a best-fit age of 460 ka and inheritance $3.8 \times 10^5$ at.g$^{-1}$(SiO$_2$) (star).

Figure 10: Weighted mean $^{10}$Be CRE age of T3 tread including the surface sample exposure ages of North and South sites and excluding outlier sample DN06S2. The thin curves represent the CRE age probability as Gaussian distribution for each individual sample and the thick curves correspond to the summed Gaussian density probability function. The weighted mean age is obtained with errors equal to two standard deviations (2 $\sigma$).

Figure 11: a) Weighted mean CRE age for the $^{10}$Be and $^{36}$Cl surface samples collected on T2 tread at Dehshir South site. The ages have been calculated assuming no erosion and no inheritance and the sample DS08S114 (49.9 ± 3.3 ka) has not been included in the statistics. The thin curves represent the CRE age probability as Gaussian distribution for each individual sample and the thick curves correspond to the summed Gaussian density probability function. The weighted mean age is obtained with errors equal to two standard deviations (2 $\sigma$). b) Field photograph showing the 4m high T2/T0 riser sampled for profile PS1 (see Figure 2 for location). c) Profile of $^{10}$Be concentrations through the terrace T2 at site PS1. Red and blue dots are surface and near-surface samples, respectively. The two OSL samples collected by
the same riser along strike within sandy lenses are indicated. Dashed curves represent the forward models of theoretical $^{10}$Be near-surface concentration for a 30 ka abandonment age assuming homogeneous inheritances of $3.5 \times 10^5$ at.g$^{-1}$(SiO$_2$) (left) and $9 \times 10^5$ at.g$^{-1}$(SiO$_2$) (right).

Figure 12: Plot of the measured $^{10}$Be concentrations as a function of depth (left panel) and simplified stratigraphy (right panel) through profile PS2. Depth profile PS2 has been excavated within T2 tread, North of the Marvast River (see location on figure 2). Relative positions of OSL samples AB/2006/I and II and CRE near-surface amalgams are shown (blacks arrows).

Figure 13: Synthesis of observations and plot of sample ages in relative position from north to south for site Dehshir North (left panels) and site Dehshir South (right panels). Dots and errors bars are in red, blue and black for $^{10}$Be, $^{36}$Cl and OSL dating, respectively. a) The thick lines and shaded regions are the weighted mean with 2$\sigma$ confidence interval for the CRE surface age. Samples DN06S2 and DN08S114 have been omitted for the T3 and T2 statistics, respectively. The thin lines are the oldest possible CRE age of the youngest CRE sample collected on the terrace treads. b) Upper part, relative positions and OSL ages of the samples collected below the terrace treads of T2, T1b and T1a. Samples HI (Nazari et al., 2009; Fattahi et al., 2010) and AB have been collected within trenches excavated for paleoseismic purposes and samples OSL I-IV by the terrace risers. Lower part, CRE and OSL ages available for terraces T2 and T1. The thick black line is the oldest possible age of the most surficial OSL sample collected below each terrace tread.

Figure 14: Depth-profile PS1 and PN of $^{10}$Be concentrations respectively through terrace T2 (a) and T3 (b). Violet and red dots are the measured concentrations of the near-surface amalgams and surface samples, respectively. Blue dots and black dots are the respective concentrations of the near-surface amalgams and surface samples once one near-surface amalgam is restored to a null concentration without bringing back any other near-surface sample to a negative concentration (see text for discussion). The time of in-situ exposure to bring that near-surface sample to its measured concentration is indicated in red, and the residual concentrations remaining in the other near-surface samples by black arrows materializing the sample inheritance for such duration of exposure. The only rejuvenated surface sample displaying a negative concentration is the sample DN06S2 on T3, therefore a
statistical and physical outlier for a 412 ka exposure age. This race to zero-concentration for
the near-surface amalgams indicates that T2 and T3 have to be younger than 107 ka and 412
ka, respectively. Shaded area corresponds to physically unrealistic domains of negative $^{10}$Be
concentrations.

Figure 15: Summary of offsets and ages available to assess the slip-rate of the Dehshir fault.

Table 1: The $^{10}$Be and $^{36}$Cl nuclide concentrations and CRE modelled ages for surface and
near-surface samples along the Dehshir fault. Propagated analytical uncertainties include error
blank, carrier and counting statistics. Zero erosion model ages are calculated for surface
samples with propagated analytical uncertainties, including error blank, carrier and counting
statistic; corresponding geographic correction factors and without shielding in agreement with
site topography. $^{10}$Be and $^{36}$Cl half-life are respectively 1.387 Ma (Chmeleff et al., 2010;
Korshincek et al., 2010) and 301 ka (Gosse & Philipps, 2001). For surface samples, a density
of 2.2 g.cm$^{-3}$ and 2 g.cm$^{-3}$ have been used for quartz and carbonates samples respectively. An
attenuation length of 160 g.cm$^{-2}$ (Gosse & Philipps, 2001) has been used. Stone (2000)
polynomial has been used to determine surficial production rate assuming a SLHL production
rate of 4.49 at.g$^{-1}$.yr$^{-1}$ for $^{10}$Be with 6% of uncertainty. The $^{36}$Cl production rate of 48.8 ± 3.4
at.g$^{-1}$.yr$^{-1}$ is from Stone (1996). $^{10}$Be ages have been calculated using Cosmocalc (Vermeesh
2007). $^{36}$Cl ages have been calculated using Excel spreadsheet of Schimmelpfening et al.
(2009). N.M means no or incoherent measure. Maximum erosion rates have been calculated
for the surface cobbles collected on T3 tread, with an infinite time of exposure hence at the
steady state equilibrium. About 20-30 pebbles with centimetre size have been generally
collected for the amalgamated samples of the profiles. For the T2/T0 riser profile, the
amalgams are made of a dozen of larger cobbles.
Table 2: Mean chemical composition of the samples collected for $^{36}$Cl dating. Measurements of the major elements were undertaken at the SARM facility (Nancy, France).

Table 3: Equivalent dose ($D_e$), annual dose rate ($D_a$) and calculated OSL ages for each sample. The weighted mean ages published in Nazari et al. (2009) have been refined following the statistical analysis used by Fattahi et al (2010) to account for partial bleaching. Ages have been calculated for Quartz grains with size ranging between 90 and 150 microns.
Figure 5

a)

b)

c)

d) NE SW
**Figure 6**

**Dehshir North**

---

**a)**

![Diagram showing ages and distances](image)

- $^{10}$Be: 423.44 ka, 371.12 ka, 133.95 ka, 82.38 ka
- $^{36}$Cl: 235.12 ka, 270.93 ka, 200.17 ka
- $^{10}$Be: 257.35 ka, 225.75 ka, 84.56 ka, 61.62 ka, 57.11 ka, 51.28 ka

---

**Approximate distance along the fault from north to south**

---

**b)**

- **$^{10}$Be**
  - 462 ± 55 ka

- **$^{36}$Cl**
  - 325 ± 74 ka
Figure 7
Dehshir South

\[\begin{align*}
^{10}\text{Be} & \quad 318.70 \text{ ka} \\
^{36}\text{Cl} & \quad 29.95 \text{ ka} \\
^{10}\text{Be} & \quad 211.14 \text{ ka} \\
^{36}\text{Cl} & \quad 93.89 \text{ ka} \\
^{10}\text{Be} & \quad 46.58 \text{ ka} \\
^{36}\text{Cl} & \quad 625.82 \text{ ka} \\
^{10}\text{Be} & \quad 380.20 \text{ ka} \\
^{36}\text{Cl} & \quad 237.16 \text{ ka}
\end{align*}\]

Approximate distance along the fault from north to south

a)  

b)  
\[\begin{align*}
^{10}\text{Be} & \quad 481 \pm 119 \text{ ka} \\
^{36}\text{Cl} & \quad 344 \pm 83 \text{ ka}
\end{align*}\]
Figure 8

Surface samples

Concentration $^{36}\text{Cl}$ (at/g sample x $10^7$)

Near-surface samples

Surface sample

Near-surface sample

- Density 2 g/cm$^3$
  - $\varepsilon = 1.90$ m/Ma
  - no inheritance
  - $t = 3$ Ma

- Density 2.2 g/cm$^3$
  - $\varepsilon = 1.48$ m/Ma
  - no inheritance
  - $t = 3$ Ma

- Density 2.4 g/cm$^3$
  - $\varepsilon = 1.18$ m/Ma
  - no inheritance
  - $t = 3$ Ma
Figure 9

a) Surface samples

Concentration \(^{10}\text{Be}\) (at/g (SiO\(_2\) \(\times 10^6\))

Near-surface samples

\(\chi^2 = 931\)

no erosion

3.8 \(\times 10^5\) at/g

t = 464 ka

\(\chi^2 = 2412\)

no erosion

no inheritance

t = 686 ka

\(\chi^2 = 3054\)

no erosion

7.6 \(\times 10^5\) at/g

t = 327 ka

Surface sample

Near-surface sample

b) No erosion

\(\chi^2 = 931\) (log \(\chi^2 = 2.97\))

t = 460 ka

h = 3.8 \(\times 10^5\) at/g
Figure 10

T3 tread

469 ± 88 ka
Figure 11

(a) Concentration $^{10}$Be (at/g (SiO$_2$) x 10$^6$) vs. Depth (cm)

(b) Surface sample T2 Dehshir south

175 ± 62 ka

(c) Concentration $^{10}$Be (at/g (SiO$_2$) x 10$^6$)

Surface samples

Near-surface samples

OSL I

OSL II

Depth (cm)

Surface samples

Near-surface samples
Concentration $^{10}\text{Be} \text{ (at/g (SiO}_2\text{)} \times 10^6)$

Profile PS2, Dehshir south T2

a) Concentration $^{10}\text{Be}$ (at/g (SiO$_2$) x 10$^6$)

Depth (cm)

0 50 100 150 200 250 300 350

b) Angular gravely sands
stratified fine sands, silts and clays
Angular gravely sands
gypsum
Coarse sands with silty matrix
gravelly sands and channels
coarse sands and sandy lenses
indurated level of gravelly sands and carbonates

Figure 12
Figure 14

a)  

![Graph a) showing 10Be concentration (at/g SiO₂) with depth (cm) and data points indicating exposure times and inheritance amounts.]

- Dehshir South T2
  - Near-surface sample
  - Near-surface sample with rejuvenation of 107 ka
  - Surface sample
  - Surface sample with rejuvenation of 107 ka
  - Exposure of 107 ka
  - Amount of inheritance in each sample emplaced 107 ka ago

b)  

![Graph b) showing 10Be concentration (at/g SiO₂) with depth (cm) and data points indicating exposure times and inheritance amounts.]

- Dehshir North T3
  - Near-surface sample
  - Near-surface sample with rejuvenation of 412 ka
  - Surface sample
  - Surface sample with rejuvenation of 412 ka
  - Exposure of 412 ka
  - Amount of inheritance in each sample emplaced 412 ka ago
2 fragments of the same gel-shaped cobble (15 cm) in the river bed

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Density scaling

Cl maximum 383,5

Be no erosion 36

Cl maximum 38

Be no erosion 36
### Sample Description

**T0**
- 2 fragments of the same gelyfracted cobble (15 cm)
- 1 fragment of a gelyfracted cobble (15 cm)
- Cobble (10 cm) in the river bed
- Cobble (10 cm) in the river bed
- Cobble (15 cm)
- Cobble (15 cm)
- Cobble (10 cm)
- Cobble (10 cm)
- Cobble (20 cm)
- Cobble (20 cm)
- Cobble (10 cm)
- Cobble (10 cm)
- Cobble (10 cm)
- Cobble (10 cm)
- Cobble (10 cm)

**T1**
- 2 fragments of the same gelyfracted cobble (15 cm)
- 1 fragment of a gelyfracted cobble (15 cm)
- Cobble (10 cm) in the river bed
- Cobble (10 cm) in the river bed
- Cobble (15 cm)
- Cobble (15 cm)
- Cobble (10 cm)
- Cobble (10 cm)
- Cobble (20 cm)
- Cobble (20 cm)
- Cobble (10 cm)
- Cobble (10 cm)
- Cobble (10 cm)
- Cobble (10 cm)

**T2**
- 2 fragments of the same gelyfracted cobble (15 cm)
- 1 fragment of a gelyfracted cobble (15 cm)
- Cobble (10 cm) in the river bed
- Cobble (10 cm) in the river bed
- Cobble (15 cm)
- Cobble (15 cm)
- Cobble (10 cm)
- Cobble (10 cm)
- Cobble (20 cm)
- Cobble (20 cm)
- Cobble (10 cm)
- Cobble (10 cm)
- Cobble (10 cm)

**T3**
- 2 fragments of the same gelyfractured cobble (15 cm)
- 1 fragment of a gelyfractured cobble (15 cm)
- Cobble (10 cm) in the river bed
- Cobble (10 cm) in the river bed
- Cobble (15 cm)
- Cobble (15 cm)
- Cobble (10 cm)
- Cobble (10 cm)
- Cobble (20 cm)
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- Cobble (10 cm)
- Cobble (10 cm)

### Density

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### Sample Description Information

- **Sample ID:** DS06S110, DS06S111, DS06S124, DS06S125, DS08S113, DS08S111, DS08S123, DS08S124
- **Location:** Dehshir, T3

---

**Note:**
- The table presents data on the physical properties of the samples, including density, thickness, and geographical coordinates. The data is crucial for understanding the geological context of the samples.
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Note: The table above contains data related to soil samples with their respective latitudes, elevations, and measured isotopic abundances. The Be and Cl model ages, as well as no erosion and erosion rates, are also listed. The samples are from different locations, indicated by their respective identifiers in the first column.
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*Finite Mixture Modelling (Roberts et al 2000) of replicate De values only undertaken where De distributions were multimodal, skewed and/or scattered (see text for details).

Age based on De determined using Central age Model (CAM; Galbraith et al. 1999).

Age based on De determined using Finite mixture Modeling (FMM; Roberts et al 2000).