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Dating desert pavements -

First results from a challenging environmental archive

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Abstract

Desert pavements are widespread landforms of arid environments. They consist of a monolayer of clasts at the surface, associated with an underlying unit of eolian fines. In some situations, buried desert pavements can be observed, which is interpreted as a change in the environmental conditions. Therefore, it is believed that desert pavements represent important paleoenvironmental sediment archives, especially for arid environments, where natural archives of past environments are rare. To better understand the formation process of desert pavements and to enable the paleoenvironmental interpretation of these valuable sediment archives, reliable chronologies are of crucial importance. Thus, OSL dating was applied to samples from well-developed desert pavements in two different study areas, the Cima Volcanic Field, eastern Mojave Desert, USA, and the desert of northeastern Badia, Jordan. To test the suitability of the sediments for OSL dating, the luminescence characteristics of the fine- and coarse-grain quartz fraction are described and compared. Finally, first OSL ages are presented.

1. Introduction

Desert pavements are typical geomorphological features in arid environments (Goudie, 2013). They are composed of a monolayer of clasts at the surface, associated with an underlying unit of eolian fines (sandy silt), which exhibits a several centimeter thick foamy pore structure directly beneath the clasts, the vesicular horizon (Springer, 1958; McFadden et al., 1998; Anderson et al., 2002; Dietze et al., 2012). Desert pavements form by dust trapping, causing vertical accretionary rise above a thickening eolian mantle (Mabutt, 1977; McFadden et al., 1986; Gerson and Amit, 1987). In some situations, the described sediment succession of pavement clasts and eolian mantle is underlain by another sediment unit of equal succession, interpreted as a buried desert pavement (Dietze et al., 2011; Dietze and Kleber, 2012; Dietze et al., 2013). It is believed that changes in the environmental conditions, e. g. variations in precipitation, dust flux or vegetation cover, are responsible for the changes in the rate of desert pavement aggradation or its burial (Dietze et al., 2013). In this sense, the sediment units of desert pavements represent important paleoenvironmental sediment archives, especially for arid environments, where natural archives of past environments are rare.

To better understand the formation process of desert pavements and its boundary conditions (precipitation, dust flux, vegetation etc.) and to enable the paleoenvironmental interpretation of these valuable sediment archives, reliable chronologies are of crucial importance. So far, the age of desert pavements, defined as the beginning of eolian fine accumulation beneath the clasts, were dominantly estimated using relative age indicators such as geomorphological and pedological parameters (Wells et al., 1985). However, Dietze et al. (2011) demonstrate that these relative age indicators are problematic, because there is no direct relationship between the surface properties, soil development and the age of desert pavements. Numerical dating of the clasts of desert pavements using cosmogenic ^3He and ^{10}Be surface exposure dating was e. g. applied by Wells et al. (1995) and Matmon et al. (2009), with a focus on dating the beginning of desert pavement formation and investigating their surface stability over time. However, the process of dust trapping and therefore the

dating of the eolian fines below the desert pavement can best be dated by luminescence dating techniques (Aitken, 1985). This technique enables the direct dating of sediment deposition and therefore sheds light on the process and the paleoenvironmental conditions of desert pavement formation, as well as on its rate of formation.

Even though desert pavements are global phenomena of arid landscapes, there are only a very limited number of studies where luminescence dating was applied to decipher the chronology of these valuable sediment archives. Anderson et al. (2002), Wells et al. (1995) and McFadden et al. (1998) applied thermoluminescence dating (TL) on desert pavements in the Mojave desert, USA, while Matmon et al. (2009) used optically stimulated luminescence dating (OSL) for their investigations in the Negev desert of southern Israel. However, in all of these studies, the dating results are presented, but no details about the luminescence characteristics are given and discussed.

In this study we investigate the suitability of desert pavement eolian fines for OSL dating from two different study areas. From both study areas, the Mojave Desert, USA, and the desert of northeastern Badia, Jordan, fine- and coarse-grain quartz samples were used for OSL measurement and OSL characterization. Finally, first OSL ages from both grain sizes are presented, which lead to a new view on the formation of desert pavements and its environmental boundary conditions.

2. Study area

For this study, samples from two arid landscapes with well-developed desert pavements were used. The first study area is located in the Cima Volcanic Field, eastern Mojave Desert, southwestern USA (Fig. 1). There, one sediment profile (CVF07-002; cf. (Dietze and Kleber, 2012)) on a 560 ± 80 ka old basalt flow (Turrin et al., 1985) was sampled. The profile is situated on a gently inclined slope, at an altitude of ca. 900 m a.s.l., and possible dust sources for desert pavement development are represented by numerous playas situated in the vicinity of the Cima Volcanic Field. Annual precipitation varies between ca. 69 mm in

Baker (320 m a.s.l.) and 160 mm in Yucca Grove (1204 m a.s.l.). The same climate stations record annual air temperatures of 21°C and 14.7°C, respectively. The precipitation and temperature is mainly controlled by topography and elevation, with dominantly winter precipitation associated with southwestern storm fronts (Koehler et al., 2005). In total, four OSL samples were analyzed from the profile, all taken from the eolian fines below the desert pavement and below the vesicular horizon (Fig. 2). Sample GI70 was taken in 15 cm, sample GI71 in 33 cm, sample GI72 in 53 cm and sample GI73 in 74 cm depth.

The second study area is located in the desert of northeastern Badia, Jordan (Fig. 3). This desert is again characterized by well-developed desert pavements, even though their eolian fines are less thickly developed (ca. 30-80 cm) than the ones from the Mojave Desert (ca. 80-120 cm). In Jordan, three sediment profiles were investigated, with sample GI54 (22 cm), GI55 (35 cm) and GI56 (50 cm) from profile JO13, sample GI57 (30 cm) and GI58 (50 cm) from profile JO14 and finally GI59 (30 cm) from profile JO15. Again, OSL samples were taken from the eolian fines below the desert pavement and below the vesicular horizon (Fig. 4). All investigated profiles are situated on gently inclined slopes, at an altitude of 700 m to 850 m a.s.l., and were developed on basaltic lava flows with ages between 0.15 Ma and 14 Ma. Possible dust sources for desert pavement development are the playas in the eastern and southern part of the northeastern Jordan Badia desert, but also long-distance dust from the northeastern African desert regions (Yaalon and Ganor, 1973). Annual precipitation in the northeastern Jordan Badia is about 75 mm, with a mean annual air temperature of ca. 22°C (Al-Qudah and Abu-Jaber, 2009).

3. OSL sample preparation and measurement procedure

To determine the equivalent dose (D_e), the fine- (4-11 μm) and coarse-grain (90-125 μm) quartz fraction was prepared from sediment samples taken during the night from an iteratively deepened surface patch to minimize vertical sample thickness to 1-2 cm sediment sample. In a first step, the sediment was wet sieved, followed by a treatment with HCl and

H₂O₂ to remove carbonates and organics. To gain the coarse-grain fraction, density separation with lithium-heteropolytungstate (2.68 - 2.62 g/cm³) was used and afterwards the quartz extract was etched in 40% HF for 80 min, to remove the α -irradiated outer layer of the grains and to remove any feldspar contamination. In a final step, the coarse-grain quartz fraction was washed for 30 min in 10% HCl. The fine-grain fraction was separated by settling using Stokes' law. To get pure fine-grain quartz extracts, the polymineral samples were etched in 34% pre-treated H₂SiF₆ for several days (Fuchs et al., 2005). For both, the fine- and coarse-grain quartz fraction, the purity of the quartz extracts was checked by IRSL measurements and aliquots with IRSL/OSL ratios greater than 3% were rejected. All preparation steps were performed under subdued red light (640 $\pm$ 20 nm).

The luminescence measurements to determine the D_e for quartz were carried out on a *Lexsyg reader Standard* (Lomax et al., 2014). For stimulation, the reader was operated with its green LEDs (525 $\pm$ 25 nm), while for signal detection, a *Hamamatsu H7360* photomultiplier combined with a 5 mm *Semrock HC377/50* filter in combination with a 3 mm *Schott BG3* filter was applied. This combination restricts the detection window to ca. 350-400 nm, thus is centered on the main OSL emission of quartz (Huntley et al., 1991; Martini and Galli, 2007). Stimulation with IR laser diodes (850 $\pm$ 3 nm) was used to check for the purity of the quartz extracts. In this case, signals were detected through a 3.5 mm *Semrock HC414/46* interference filter in combination with a 3 mm *Schott BG39* filter, which restricts the detection window to ca. 395-430 nm. Sample irradiation was performed with a ⁹⁰Y/⁹⁰Sr β -source (1,9 GBq), resulting in a dose rate for coarse-grain quartz on stainless steel cups of ca. 0.132 $\pm$ 0.003 Gy/s. The dose rate for fine-grain quartz on stainless steel cups is ca. 0.147 $\pm$ 0.003 Gy/s.

For D_e determination of both grain sizes, a single aliquot regenerative (SAR) protocol after Murray and Wintle (2000) was applied. To define the samples' dose-response, six regeneration cycles were used. The shine-down curves were measured for 50 s at elevated temperatures (125°C) after a preheat of 260°C (10 s) and a cut-heat of 220°C for the natural and regeneration signals. The preheat and cut-heat temperatures were chosen after preheat

plateau test measurements and dose recovery tests for which the samples were bleached in the Lexsyg reader using the green LEDs and irradiated with a known β -dose close to the natural dose.

For D_e determination, the integral of the first 0.5 s of the quartz shine-down curves was used, after subtracting a background of 40 to 50 s from the signal. Feldspar contamination of the quartz extracts was checked by IR stimulation after artificial dosing. Small aliquots were used for D_e determination of the coarse-grain fraction, with 2 mm aliquots (ca. 200 grains) for the samples from the Jordan desert and, due to lacking signal intensity, 4 mm (ca. 600 grains) for the samples from the Mojave Desert. In general, up to 28 aliquots were measured for each coarse-grain sample and six aliquots for each fine-grain sample to determine the D_e . After passing the rejection criteria of 10% for the recycling ratio, 5% for the test dose error, 5% for the recuperation value, the mean D_e from every sample was calculated using the central age model after Galbraith et al. (1999).

The dose rate ($\dot{D}$) for OSL age calculation was determined by thick source α -counting and ICP-MS. Cosmic-ray dose rates were calculated according to Prescott and Hutton (1994), and an a-value of 0.035 was applied for fine-grain quartz (Mauz et al., 2006). The water content of the samples was set to 7 ± 5 %. This value and its error represent the possible water content range, based on the porosity of the sample. The used water content values were checked by measuring the in situ water contents of the samples, showing conformity within the given errors.

4. Results and discussion

4.1. Cima Volcanic Field

The samples from the Mojave Desert show relatively dim OSL signals in comparison to the samples from the Jordan Desert (Fig. 5). Therefore, 4 mm instead of 2 mm aliquot were used for D_e determination of the coarse-grain fraction. In consequence, for the majority of the measured aliquots, the OSL signals were sufficiently bright to determine a precise D_e . Both

grain size fractions show rapidly decaying OSL shine-down curves (Fig. 5), suggesting a dominant fast component contributing to the signal. This was further confirmed by component fitting of the OSL signal, even though a small medium component is detectable (Fig 5). However, due to the OSL characteristics, precise growth curves were fitted with a single saturating exponential function, showing individual saturating behavior and therefore individual D_0 values (Fig. 5). The suitability of the applied SAR protocol (Murray and Wintle, 2000) is demonstrated by positive dose recovery tests, where the given dose could be reproduced within 10% errors. In addition, a preheat plateau test was applied to evaluate the most appropriate preheat and cut-heat temperatures. Finally the identification of typical quartz 110°C TL peaks and the absence of IRSL signals confirms the purity of the quartz, showing that both, the fine- and coarse-grain samples are suitable for D_e determination (Fig. 5).

The D_e distributions of the coarse-grain samples are wide, positively skewed, bimodal for some samples. In addition, the coefficient of variation v are well above 10% (Fuchs and Wagner, 2003) with an overdispersion of 17-23%, indicating a large D_e scatter (Fig. 5). This is not true for the fine-grain samples with a narrow D_e distribution and a coefficient of variation v below 10% and an overdispersion of max. 7%. This is typical for fine-grain measurements, because the large number of grains per aliquot results in an averaging effect of possible D_e variations (Fuchs and Wagner, 2003).

Based on the central age model given by Galbraith et al. (1999), OSL ages were calculated with the parameters listed in Table 1 and 2. Thereafter, the profile from the Mojave Desert with four samples yielded OSL ages for the coarse-grain fraction of 16.5 ± 1.5 ka (GI70), 17.5 ± 1.4 ka (GI71), 20.4 ± 1.6 ka (GI72) and 32.3 ± 2.6 ka (GI73). The results for the OSL age calculations of the fine-grain fraction are 14.2 ± 1.1 ka (GI70), 25.9 ± 2.0 ka (GI71), 36.6 ± 2.9 ka (GI72) and 50.9 ± 4.1 ka (GI73). All ages with their pedostratigraphy are given in Figure 2.

4.2. Badia Desert, Jordan

The brightness of the fine- and coarse-grain OSL signals from the Jordan samples differs between the individual samples and their aliquots. All OSL signals from the coarse-grain fraction show a sufficient brightness, with fast decaying OSL shine-down curves, indicating a dominant fast component, confirmed by the component fitting of the CW-OSL curves (Fig. 5). The fine-grain OSL curves decay slower, and a medium component contributes to the total signal (Fig. 5). The reason for this behavior is so far unclear and needs further evaluation. The purity of the quartz extracts is demonstrated by typical quartz TL curves with a distinct 110°C peak and by the absence of any IRSL signal. The resulting growth curves fitted with a single saturating exponential function show individual saturating behavior, thus individual D_0 values, and could be established with high precision (Fig. 5). Finally, the outcome of positive dose recovery tests, where the given dose could be reproduced within 10% errors and positive preheat plateau tests demonstrate the general suitability of the applied SAR protocol for both, the fine- and coarse-grain samples.

The coarse-grain samples show a broad D_e distribution with a coefficient of variation v well above 10% (Fuchs and Wagner, 2003) and an overdispersion of 24-38%. The distributions are generally skewed to smaller D_e values (Fig. 5), in some cases bimodal. In contrast, the fine-grain samples show a narrow D_e distribution with a coefficient of variation v well below 10% and an overdispersion of max. 6%, again caused by the large number of grains per aliquot (Fuchs and Wagner, 2003).

The OSL ages were calculated applying the central age model after Galbraith et al. (1999). The analytical data for OSL age calculation, including the data for dose rate determination are given in Table 1 and 2. In Figure 4, the ages are presented with their pedostratigraphic context. Thereafter, for profile JO13 with three samples, coarse-grain OSL ages of 16.8 ± 1.7 ka (GI54), 39.3 ± 3.8 ka (GI55) and 65.0 ± 6.0 ka (GI56) were calculated. The corresponding fine-grain OSL calculations yielded ages of 27.2 ± 2.2 ka (GI54) and 51.0 ± 4.4 ka (GI55). Due to a shortage of sample material, no fine-grain age for sample GI56 could be determined. From profile JO14, two samples with coarse-grain ages of 52.6 ± 5.9 ka (GI57) and 73.7 ± 6.6 ka (GI58) were obtained, and corresponding fine-grain ages of 60.6 ± 5.1 ka

(GI57) and 82.4 ± 7.4 ka (GI58). A single sample from profile JO15 yielded a coarse-grain age of 63.2 ± 6.7 ka (GI59), with a fine-grain age of 75.5 ± 6.7 ka respectively.

4.3. Discussion of OSL results

From both study areas, all coarse-grain quartz samples show a broad D_e distribution with a coefficient of variation v well above 10% (Fuchs and Wagner, 2003) and an overdispersion of 17-38%. This is surprising, because it is thought that due to the eolian origin of the sand, all mineral grains should be well bleached due to the single grain eolian transport and the generally bright light conditions in arid environments. This asks for another explanations for the broad D_e distribution. These might be quartz inherent variations, such as varying proportions of the fast and medium component in the initial signal or external sources of variations such as bioturbation or formation dynamic of the desert pavement itself. Differing proportions of fast and medium components in the initial signal cannot be excluded, but at least for the coarse-grain Jordan samples it does not seem to be the main reason, as these samples are dominated by the fast component (Fig. 5). Bioturbation as a possible explanation for the broad D_e distribution is unlikely, because this process would destroy the vesicular horizon and this was not observed for the investigated sites. The formation process of the desert pavement itself is an alternative explanation for varying D_e values in a sample. A possible scenario is that after the sand grains get trapped between the rough surface of the desert pavement, the coarse grains migrate via cracks into the underlying unit of eolian fines, where they get mixed with older deposits (Anderson et al., 2002).

In contrast to the coarse-grain fraction, the D_e distributions of the fine-grain fraction from both study areas are characterized by a coefficient of variation v below 10% and an overdispersion of max. 7% (Fig. 5). However, this is not necessarily indicative of well-bleached samples, because the large number of grains per aliquot results in an averaging effect of possible D_e variations (Fuchs and Wagner, 2003). The calculated OSL ages from

the fine-grain fraction are, except for one sample (GI70), systematically older than the OSL ages from the coarse-grain fraction. In case of the Jordan samples, fine-grain OSL ages are significantly older by ca. 10 ka. In case of the samples from the Mojave Desert, the age discrepancy increases with depth and ranges from ca. 8 ka to 18 ka. The reason for the age differences between the grain sizes is unknown, but differences in the luminescence properties are possible explanations, as well as different effects of the formation processes of the desert pavement on individual grain sizes.

Different luminescence properties between the two grain size fractions as a reason cannot be ruled out. First, the fine-grain signals do show a greater proportion of the medium component to the initial (natural) signal. To decrease the consequences of this different proportion, it can be advisable to use an early background (EBG) subtraction for the fine-grain samples (Ballarini et al., 2007; Cunningham and Wallinga, 2010). To test the effect of an EBG subtraction, we calculated fine grain ages using an initial signal of the first second subtracted by a background of the signal between 2 and 5 seconds. The late background and EBG ages are indistinguishable from each other and the age discrepancy to the coarse-grain ages still exists, independently of the analyzed integrals. Second, age discrepancies between the coarse- and the fine-grain fraction have been noted before and are e.g. a widespread problem in southeastern European loess (Timar-Gabor et al., 2012; Anechitei-Deacu et al., 2014; Constantin et al., 2014). In those studies, however, the fine-grain ages were significantly younger than the coarse-grain ages. The reason for the age discrepancies in these loess samples remains unexplained so far. It thus becomes clear, from this and from other studies, that further investigations are needed to explain different luminescence ages in different grain size fractions.

An alternative reason for the age differences between the coarse- and fine-grain fractions is the formation process of the desert pavement itself. A possible explanation would be that the sand fraction (coarse-grain) gets incorporated via vertical cracks into the eolian fines below the desert pavement at a later stage than the deposition of the underlying silt fraction (fine-grain). Thereafter, the silt fraction is continuously deposited (long-distance sediment

transport) in contrast to discontinuous and possibly pulsed deposition of the sand fraction from nearby sediment sources. However, this hypothesis needs further exploration, including higher resolved chronologies to establish more robust deposition rate estimates.

5. Conclusions

Eolian fines from desert pavements in the Mojave Desert, USA, and from the northeastern Badia desert, Jordan, were sampled for OSL dating and for luminescence characterization. Two grain sizes, the fine- and coarse-grain quartz fractions were analyzed and compared. The grain size fractions from both study areas show adequate luminescence characteristics for OSL dating, with typical quartz behavior, even though a small medium component was detectable for most of the samples. Nevertheless, precise growth curves and D_e calculations were possible, with narrow D_e distribution for the fine-grain samples and broad distributions for the coarse-grain samples. Due to the eolian origin of the sediments, we argue for well-bleached samples and conclude that next to quartz inherent variations, the formation process of the desert pavement itself might cause the broad D_e distribution obtained for the coarse-grain fraction. The calculated OSL ages show significant differences between the fine- and coarse-grain fraction. This can again be explained by the formation process of the desert pavements itself, with continuous deposition of the silt fraction (fine grain) and a subsequent deposition of the sand fraction (coarse grain), migrating via cracks into the underlying unit of eolian fines. Based on these first and promising OSL ages from desert pavements in Jordan and the Mojave Desert / USA, we believe that these sediment archives have a great potential for reconstructing paleoenvironments, especially in arid environments, where natural archives of past environments are rare.

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Table 1:

Analytical data: Sample code, ^{238}U , ^{232}Th and ^{40}K -concentrations and total dose rate for fine- (CG) and coarse-grain (CG) quartz samples.

Sample	U [ppm]	Th [ppm]	K [%]	$\dot{D}$ [Gy/ka]	
				FG Quartz	CG Quartz
<i>Jordan</i>					
<i>GI54</i>	2.28 ± 0.17	3.24 ± 0.54	0.89 ± 0.05	2.11 ± 0.16	1.79 ± 0.10
<i>GI55</i>	2.38 ± 0.18	3.71 ± 0.58	0.84 ± 0.04	2.13 ± 0.16	1.79 ± 0.10
<i>GI56</i>	2.11 ± 0.25	5.31 ± 0.83	0.81 ± 0.04	2.17 ± 0.19	1.81 ± 0.12
<i>GI57</i>	1.83 ± 0.18	4.11 ± 0.58	0.87 ± 0.04	2.03 ± 0.15	1.73 ± 0.10
<i>GI58</i>	1.98 ± 0.18	3.95 ± 0.58	0.72 ± 0.04	1.91 ± 0.15	1.60 ± 0.10
<i>GI59</i>	1.74 ± 0.17	2.96 ± 0.30	0.72 ± 0.04	1.75 ± 0.13	1.48 ± 0.09
<i>USA</i>					
<i>GI70</i>	2.82 ± 0.21	7.90 ± 0.69	2.16 ± 0.10	3.96 ± 0.26	3.43 ± 0.20
<i>GI71</i>	3.35 ± 0.27	10.55 ± 0.89	2.66 ± 0.13	4.85 ± 0.33	4.19 ± 0.25
<i>GI72</i>	3.33 ± 0.28	11.34 ± 0.92	2.69 ± 0.13	4.94 ± 0.33	4.26 ± 0.26
<i>GI73</i>	3.21 ± 0.29	12.66 ± 0.97	2.48 ± 0.12	4.82 ± 0.33	4.12 ± 0.25

Note: For dose rate calculation a water content of $7 \pm 5\%$ was used. The α -value of 0.035 for fine grain quartz dose rate determination was applied (Mauz et al., 2006).

Table 2:

Analytical data: Sample code, sampling depth, equivalent dose and OSL ages for fine- (CG) and coarse-grain (CG) quartz samples.

Sample	Profile	Depth [cm]	D_e [Gy]		OSL Age [ka]	
			FG Quartz	CG Quartz	FG Quartz	CG Quartz
<i>Jordan</i>						
<i>GI54</i>	JO13	22	57.50 ± 2.10	30.00 ± 2.40	27.2 ± 2.2	16.8 ± 1.7
<i>GI55</i>		35	108.70 ± 4.50	70.34 ± 5.32	51.0 ± 4.4	39.3 ± 3.8
<i>GI56</i>		50	no value	117.30 ± 7.70	no value	65.0 ± 6.0
<i>GI57</i>	JO14	30	123.00 ± 4.50	90.80 ± 8.50	60.6 ± 5.1	52.6 ± 5.9
<i>GI58</i>		50	157.30 ± 6.90	117.80 ± 7.90	82.4 ± 7.4	73.7 ± 6.6
<i>GI59</i>	JO15	30	131.80 ± 5.90	93.70 ± 8.20	75.5 ± 6.7	63.2 ± 6.7
<i>USA</i>						
<i>GI70</i>	CVF07:002	15	14.22 ± 1.14	56.50 ± 3.80	14.2 ± 1.1	16.5 ± 1.5
<i>GI71</i>		33	25.86 ± 2.04	73.00 ± 3.70	25.9 ± 2.0	17.5 ± 1.4
<i>GI72</i>		53	36.59 ± 2.93	86.90 ± 4.40	36.6 ± 2.9	20.4 ± 1.6
<i>GI73</i>		74	50.87 ± 4.11	133.00 ± 7.20	50.9 ± 4.1	32.3 ± 2.6