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Research paper

Possible resetting of quartz OSL signals during earthquakes—Evidence from late Pleistocene injection dikes, Dead Sea basin, Israel

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Abstract

Clastic dikes are formed either by passive deposition of clastic material into pre-existing fissures (depositional dikes), or by fracturing and injection of clastics during earthquakes (injection dikes). We proposed to use optically stimulated luminescence (OSL) dating to distinguish between the two modes of formation and hypothesized that (1) depositional dikes filled from above show OSL ages younger than the host rock; and (2) injection dikes filled from below show the same OSL ages as that of the host rock. We studied the mechanisms of clastic-dike formation and their ages within the seismically active Dead Sea basin, where hundreds of dikes crosscut the late Pleistocene (~70–15 ka) lacustrine sediments of the Lisan Formation. Field observations and analysis of magnetic tensors show unequivocally that most of these dikes were emplaced by injection, inferred to be due to seismically triggered fluidization–liquefaction during earthquakes. Twenty-eight samples were collected from the Lisan source material and dikes that, based on field observations, are unmistakably either depositional dikes or injection dikes.

Quartz single aliquot OSL ages of the source Lisan layers are between 43 and 34 ka, and are typical for the Lisan Formation. The ages of both depositional and injection dikes are between 15 and 17 ka, younger than the Lisan host rock. Depositional dikes show a highly scattered distribution of single grain ages, suggesting several episodes of infill. Single grain ages of injection dikes are of latest Pleistocene to Holocene, and do not contain recently bleached grains that infiltrated from above. These results imply that the OSL signals were reset at the time of fluidization–liquefaction and buildup of fluid pressure within the injection dikes. If this resetting mechanism has a physical ground, then OSL dating is an important tool for constraining the ages of earthquake-induced injection dikes and recovering paleoseismic data from them.

Keywords: Clastic dikes; Injection structures; Luminescence dating; Dead Sea Transform

1. Introduction

Clastic dikes are sub-vertical sheets of sediment contained within a host rock. They occur in a wide range of settings, either isolated or in swarms (Diller, 1890). While the final geometry of such structures is everywhere similar and well defined, their mode of formation varies and is commonly ambiguous (e.g., Aspler and Donaldson, 1985). These sheets of sediment may be either depositional dikes, formed by passive deposition of clastic material into pre-existing fissures (Borradaile, 1984; Eyal, 1988) or injection dikes, which formed dynamically by fracturing and injection of clastics during earthquakes (e.g., Obermeier, 1998; Galli, 2000). Injection dikes are probably the most impressive liquefaction features occurring during strong $M \geqslant 6.5$ earthquakes (McCalpin, 1996; Galli, 2000). They correspond to episodic pulses of an increasing hydraulic pressure generated mostly by seismic loading during earthquakes, and were used for reconstruction of paleo-epicenter locations (McCalpin, 1996 and references therein).

In this study, we apply optically stimulated luminescence (OSL) dating (Aitken, 1998) to clastic dikes of different

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origins that crosscut late Pleistocene sediments in the Ami'az Plain, within the seismically active Dead Sea fault zone. We focused mainly on dating of injection clastic dikes, which were differentiated from depositional dikes based on field observations and their indicative magnetic fabric (Levi et al., 2006). Dating was originally applied to explore the mechanism of emplacement of the dikes, yet eventually it provided the timing of emplacement, most likely during earthquakes. Luminescence dating of fault-related sediments that post-date earthquakes has been used to construct the timing and recurrence intervals of large earthquakes and to estimate seismic hazard (e.g., Porat et al., 1996; Amit et al., 2002); however, earthquakes were not dated directly. Here we present the possibility of dating earthquake-induced structures by OSL.

2. Geologic setting

About 250 clastic dikes are exposed in the Ami'az Plain, a down-faulted block located adjacent to the Sedom Diapir (Zak, 1967; Weinberger et al., 1997) on the western margin of the Dead Sea basin (Fig. 1) (Garfunkel, 1981). The clastic dikes, previously noted by Zak (1967) and Marco

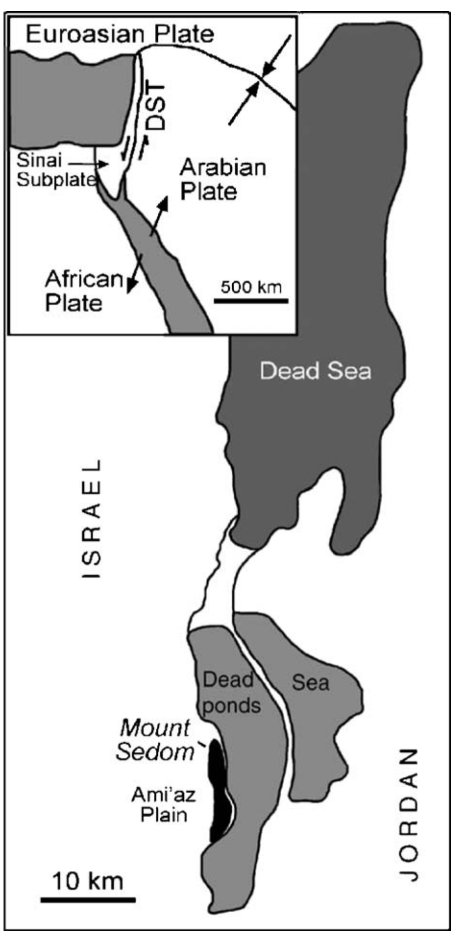

Fig. 1. Location maps showing plate boundaries (inset), the regional setting of the Dead Sea basin and the Ami'az Plain study area. DST, Dead Sea Transform (after Levi et al., 2006).

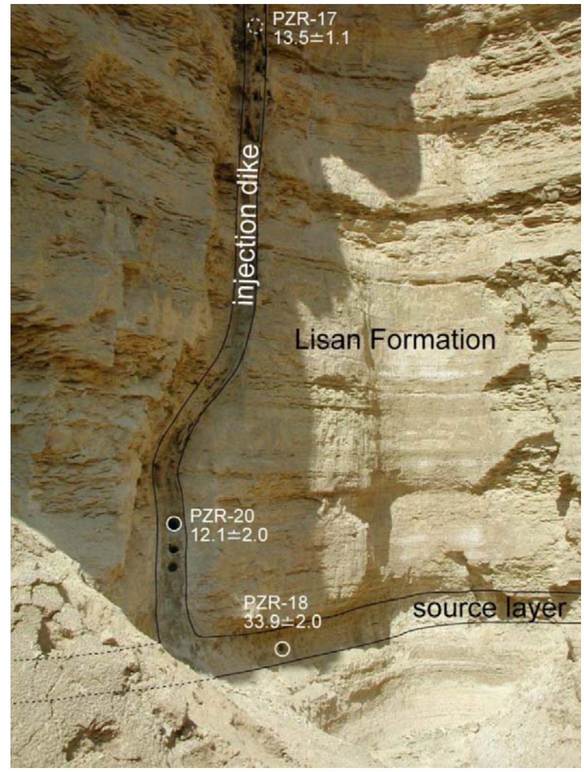

Fig. 2. A source horizontal layer and a connected vertical injection dike sampled for OSL dating. Sample numbers and ages (in ka) are indicated. Upper sampling hole (broken line) is projected from a sampling site located ~30 m away along the dike strike. Width of sampling holes is ~8 cm.

et al. (2002), are opening-mode fractures, indicating brittle fracturing of the host rock. They are up to 1 km long, at least 20 m high and up to 0.4 m wide (Fig. 2), and are arranged mainly in semi-radial and tangential geometry (Marco et al., 2002). They intruded the late Pleistocene lacustrine Lisan Formation (Begin et al., 1974). This formation consists mostly of alternating laminae of aragonite and detrital silt and clay, dated between ~70 and 15 ka by U-series and ^{14}C (Kaufman, 1971; Haase-Schramm et al., 2004). A thin veneer (<2 m) of aeolian and fluvially reworked aeolian sediments covers large parts of the plain, deposited after Lake Lisan dried out at ~15 ka. Paleoseismic records based on brecciated layers reveal the occurrence of numerous $M>5.5$–6 earthquakes during the last 70 ka in the Dead Sea basin (Marco and Agnon, 1995, Marco et al., 1996; Ken-Tor et al., 2001; Migowski et al., 2004), as well as several $M>7$ earthquakes (Begin et al., 2005).

3. Depositional dikes versus injection dikes

We distinguish between two mode of clastic-dike emplacement, depositional and injection, on the basis of field relations and indicative anisotropy in magnetic tensors (Levi et al., 2006), which yield information about the statistical alignment of magnetic particles within the rock (e.g., Tauxe, 1998).

3.1. Depositional dikes

These less abundant dikes contain brownish silt, sporadically with horizontal bedding, that resembles the brownish silt found in the local veneer of surface sediments that gravitationally filled pre-existing fissures in the Lisan Formation. These dikes always crosscut the surface and commonly have a large opening at their upper part. Analysis of magnetic tensors of depositional dikes consistently displays a magnetic fabric similar to that detected in sedimentary rocks that accumulated in low energy environments (Levi et al., 2006).

3.2. Injection dikes

More abundant are dikes composed of green clay, silty quartz and some aragonite that were derived from lower layers of the Lisan Formation (Fig. 2). In several dikes, a continuous connection between the dike-fill and a green clay-rich layer of the Lisan Formation was observed, indicating unambiguously that these structures were injected upwards from lower Lisan Formation beds. Occasionally, these dikes have a larger opening in their lower than in their upper part, and some of them do not reach the surface. At least five of these dikes are multi-phases, composed of several (3–12) distinct vertical, 20–50 mm wide, sheets of sediments.

Analysis of magnetic tensors of injection dikes consistently displays a magnetic fabric similar to that detected in magmatic dikes and flow-driven sedimentary structures. Levi et al. (2006) demonstrated that this type of magnetic fabric formed during fluidization–liquefaction of the Lisan sediments inferred to be triggered by earthquakes along the Dead Sea fault zone.

4. OSL application for clastic dikes

4.1. The hypothesis

We assumed that luminescence dating could distinguish between the two modes of dike emplacement. Depositional dikes are filled with clastics from the surface. The veneer covering the desiccated top of the Lisan comprise aeolian sediments that were deposited after 15 ka and were well bleached before getting redeposited in the fissures. Their ages would be younger than the uppermost Lisan Formation and post-date the time of fracturing. On the other hand, injection dikes are composed of deeply buried Lisan sediments, which were not exposed to sunlight after deposition. Hence, the OSL signal would not be reset and their ages would be that of the Lisan source sediments, with no relation to the age of dike emplacement.

4.2. Sampling strategy and methods

We recovered a total of 28 samples from 10 clastic dikes and four beds of the Lisan host rocks (Table S1, Appendix A). Based on field relations, the presence of bedding and color of infill, two of the dikes are depositional and six are injection dikes; the other two are most likely injection dikes but their connection to the source layer is unexposed. For comparison between the OSL ages of the injection dikes and that of the source layer, we sampled several layers in the lower section of the Lisan Formation, including a layer directly connected with an injection dike (Fig. 2).

Very-fine sand quartz (74–125 μm) was extracted from the samples using routine laboratory procedures (Porat, 2002). After wet sieving to select the desired size fraction, carbonates were dissolved using 8% hydrochloric acid and the dried fraction was passed through a Franz magnetic separator at a high current (~1.5 Amp) to remove all heavy minerals and most feldspars. The non-magnetic fraction was then etched with concentrated (42%) hydrofluoric acid for 40 min to dissolve the remaining feldspars and etch the quartz. Fluorides were removed with 16% hydrochloric acid.

4.3. Single aliquot measurements

About 5 mg of the purified quartz was deposited on 10 mm aluminum discs using silicon spray as an adhesive. Measurements were carried out in the luminescence dating laboratory at the Geological Survey of Israel (GSI), in a Risø D-12 TL/OSL reader equipped with a calibrated ^{90}Sr β source. Quartz stimulation was carried out with a green-filtered halogen bulb and detection was through 7 mm U-340 filters. Equivalent doses (De) were measured using the OSL signal and the standard single aliquot regenerative dose (SAR) protocol (Murray and Wintle, 2000) on 10–14 aliquots for each sample. Pre-heat tests were carried out to evaluate the change of De as a function of varying pre-heat temperatures between 220 and 280 °C. OSL was measured at 125 °C for 140 s to background level. Test dose was roughly 5 Gy and a cut heat of 180 °C was used to remove the 125 °C TL peak.

4.4. Single grain measurements

Single grain measurements (Bøtter-Jensen et al., 2000) were undertaken to test for mixed grain populations and to verify if there are any zero-age grains or grains with distinct Lisan ages. Four samples were selected, including injection and depositional dikes. Samples were sieved to 2 or 3 size fractions (74–90 , 90–125 and 125–150 μm) and 200 grains were measured for each fraction. As the holes in the single grain sample holder are 300 μm in diameter, on occasions as many as four grains were observed in each hole, so effectively measurements were performed on very small aliquots.

Measurements were carried out in the luminescence dating laboratory at the University of Wales, Aberystwyth, on a D-15 Single Grain Risø reader (Duller et al., 1999). A SAR protocol very similar to that used for the single aliquot measurements was used for De determinations. To prevent recuperation and buildup of background, at the end of each measurement cycle the discs were heated to 280 °C and OSL-stimulated for 100 s to background level (Murray and Wintle, 2003). Acceptance criteria for the grains followed those suggested by Jacobs et al. (2003): Signal intensity at least three times that of the background level; error on the De smaller than 30%; recycling ratio within 1 ± 0.3; an infrared stimulated luminescence (IRSL) contribution of less than 15% and a monotonously growing dose response curve. Data reduction was carried out using the *Analyst* software and various fits, and the ages were calculated using *Database* software (both programmed by G.A.T. Duller).

4.5. Dose rates

Dose rates were evaluated by both field and laboratory measurements. The γ and cosmic doses were measured in the field in the same holes from which the samples were collected, using a calibrated portable Rotem P-11 γ scintillator. Alpha and β dose rates were calculated from the concentrations of the radioelements U, Th and K, measured at the GSI in sediments collected from the same localities as the dated samples. U and Th were measured by ICP–MS while K by ICP–AES.

At the surface, the dikes and Lisan host rock are dry (1–2% water in wet sediment), however at a depth of 1 m moisture increases to ~8%. In the past, when Lake Lisan existed, the Lisan sediment was brine-saturated with water content of >40%. Since then, the Lisan sediment had gradually lost moisture up to the present water contents. At the time of dike intrusion and fracturing, the Lisan sediment must have lost enough moisture to behave as a semi-brittle host rock. After emplacement, the slurry injected into the dikes continously lost moisture up to the present water contents. Thus different parts of the Lisan and dike sections have different and complicated histories of water content. Consequently, ages for the Lisan sediment were calculated using $25 \pm 5\%$ water content and dike ages were calculated using $10 \pm 5\%$ water content, which are likely to cover the range of moisture expected throughout their history. The gamma dose rates measured in the field in the dry sediment were attenuated for the estimated moisture contents.

5. Results

5.1. Single aliquots

All tests carried out on samples perform well. Pre-heat plateau tests show that De values do not vary as a function of pre-heat temperature (Fig. S1a); dose recovery tests gave values ranging from 0.97 to 1.03; recycling ratios are all within 1 ± 0.05; recuperation is negligible and the IRSL signal contributes less than 3% to the overall OSL signal, implying that the OSL signal is dominated by quartz emission. Dose distributions of single aliquot measurements are mostly normal (Fig. S1b) with very few outlying aliquots.

The OSL ages of the Lisan host rock, between 43.2 ± 4.1 and 33.9 ± 2.0 ka (Table S2), agree with the ages obtained by U-series for the lower section of the Lisan Formation (Haase-Schramm et al., 2004), and the samples' De values are mostly in the range of 50 Gy. The youngest corrected U-series age for the Lisan Formation is 14.64 ± 0.81 ka (Haase-Schramm et al., 2004). The dike OSL ages range between 15.7 ± 1.3 and 7.2 ± 1.0 ka (Table S2) and within errors, the ages of all dikes, regardless of their proposed formation mechanism, are younger than the youngest Lisan host rock. Notably, the dike OSL ages are substantially younger than the Lisan beds at ~20 m below the surface, beds which are the source of the injection dikes. The dikes' De values are considerably lower than those of the Lisan samples, ranging between 11 and 25 Gy. Modifying the age-calculation variables within a reasonable range (i.e., moisture content, disequilibrium in the U-series, variations in cosmic dose) cannot lead to dike ages close to the age of the Lisan source material.

The scatter on the De values is mostly 5–10%, and the large uncertainties on the ages result mainly from large uncertainties in the water-content variations during the history of the samples. In fact, detailed sampling of a multiphase dike shows that OSL dating of the dikes can be precise. This dike (B3.1; Table S1) is composed of 11–12 adjacent vertical sheets of sediment that can be differentiated based on their color and texture. We interpreted these sheets as several discrete and separate episodes of injection phases, and hypothesized that the older phases would be closer to the dike margins. Eight sheets (A–H) were separated and cleaned in the laboratory and individually dated. Their ages range between 12.3 ± 1.1 and 10.9 ± 0.9 ka and their ages indeed decrease towards the center of the dike (Fig. 3). At least four injection episodes can be clearly distinguished, with only several hundred years difference between them.

5.2. Single grains

Depending on grain size fraction, 10–30% of the grains had an OSL signal that could be reliably regenerated to estimate the De values. The largest number of measurable grains was in the smaller size fraction (74–90 μm, roughly the modal grain size), probably due to simultaneous measurement of more than one quartz grain.

The average single grains De determinations for the samples are lower than the average single aliquot values, but due to the large scatter in the single grains, their age is indistinguishable from the single aliquot one (Table S3). The three injection dikes (PZR-7, PZR-11, and PZR-16)

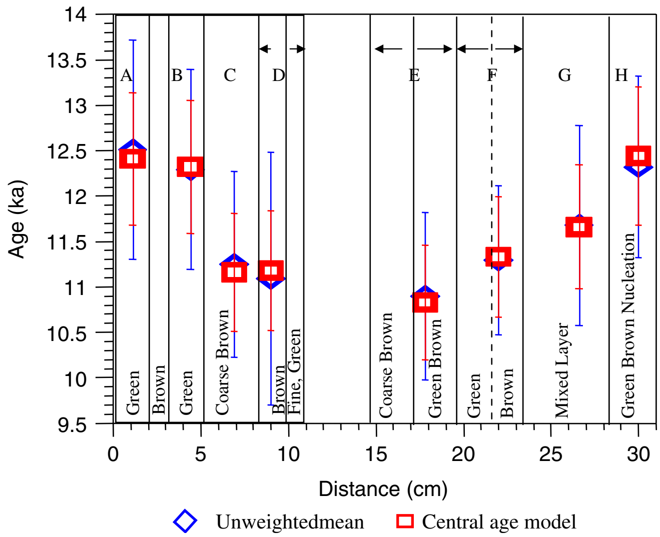

Fig. 3. Multi-phase dike. Individual phases and samples (A–H) are shown schematically. Note that some samples include more than one phase. The age for each sample is plotted as a function of distance from the left wall of the dike. See Table S2 for age calculations. While central age models reduce the scatter on the De from 5–11% to ~2%, the uncertainties on the ages are still large and all the ages overlap.

show uniform ages for all grain sizes, albeit with very large uncertainties. No grains with zero age were encountered and only a few grains with lower Lisan ages were detected. The distribution of the doses is approximate to Gaussian (Fig. S1c).

The depositional dike (PZR-14) shows a highly scattered distribution of grain De values (Fig. S1d), including a distinctly young population with an age of ~0.7 ka. This indicates that the dike formed in several episodes of infill and that as late as ~700 years ago grains from the surface infiltrated to a depth of 7 m.

6. Discussion and conclusions

Comparison of dike types with OSL ages (Tables S1 and S2) show that based on OSL ages alone, depositional dikes could not be distinguished from injection dikes in the Ami'az Plain, rejecting the hypothesized OSL ages of injection dikes. We argue that regardless of the origin a certain clastic dike had, OSL dates its emplacement time. This argument is founded on geological constrains for the time of clastic-dike emplacement, between the shrinking of Lake Lisan post 15 ka and the formation of the current landscape in the Holocene period.

The ages are firmly established; all quality-control parameters indicate that the samples perform well and that the ages are reliable. The only way to reconcile the field evidence of clastics transported from below into injection dikes, the magnetic fabric analyses showing a flow fabric, and the presented dike OSL ages, is by the resetting of the OSL signal during injection of clastics triggered by seismic shaking and fluid pressure buildup.

Banerjee et al. (1999) present a case of resetting of the TL and IRSL signals along a fault plane and show that the age of the sediment near the fault gouge is most likely that of past earthquake. Resetting took place at a depth of 2–3 km, at ambient temperatures ~100 °C and it is attributed to both thermal and pressure affects caused by displacement on the fault.

A large body of data exists on the resetting of electron spin resonance (ESR) signals on fault gouges during faulting events (Ulusoy, 2004 and references therein). Mechanical shearing and frictional heating are the responsible mechanisms for resetting of several ESR signals (Ikeya et al., 1982; Usami et al., 2005) that can be used for dating paleo-earthquakes (e.g. Lee and Yang 2003). Full signal resetting takes place at a depth of at least 100 m (Fukuchi, 1992) or 220 m (Lee and Yang, 2003). While ESR signals also result from trapped charges, their properties differ substantially from that of the luminescence signals in bleaching characteristics, thermal stabilities and level of dose saturation.

For the samples from Ami'az Plain, there is no evidence for grain size reduction in the injection dikes; the size distribution of the quartz gains in the dikes is very similar to that of the Lisan host rock; and the quartz grains are as rounded and spherical as the grains in the Lisan source layers. There is also no field evidence for any substantial heating to temperatures required to reset the OSL signals, e.g., baked margins are absent near dike walls. X-ray diffraction analyses of injection dikes do not show any mineralogical changes that can be attributed to heating: clay minerals are unchanged when compared to the Lisan source material and no anhydrite that may have formed during heating was observed (due to the extreme aridity of the study area, anhydrite is preserved over geological time scale). Indeed, there is no known heat source which could have heated the injection fluids to sufficiently high temperatures that could reset the OSL signal.

Our field observations and magnetic-fabric analyses (Levi et al., 2006) demonstrate that the formation of most clastic dikes in the Ami'az Plain is associated with fluidization–liquefaction triggered by seismic shaking of the Lisan source sediment during strong earthquakes along the Dead Sea full zone. These events occurred after deposition of the Lisan Formation, (i.e., post 15 ka). Field results support simultaneous injection of clastic materials with fracturing, and the buildup of internal fluid pressure within the fractures as evident by their geometry. Preliminary estimations of the internal pressure associated with dike intrusion, based on linear-elastic-fracture-mechanics analysis, reveal values of several MPa. Hence, we propose that during the earthquakes and subsequent fluid-pressure buildup, resetting of OSL signals probably occurred, although the zeroing mechanism remains uncertain. Further work is needed to understand this resetting mechanism.

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Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.quageo.2006.05.021.

References

Aitken, M.J., 1998. An Introduction to Optical Dating. Oxford University Press, Oxford.

Amit, R., Zilberman, E., Enzel, Y., Porat, N., 2002. Paleoseismic evidence for time dependency of seismic response on a fault system in the southern Arava Valley, Dead Sea rift, Israel. Geological Society of America Bulletin 114, 192–206.

Aspler, L.B., Donaldson, J.A., 1985. Penecontemporaneous sandstone dykes, Nonacho Basin (Early Proterozoic, Northwest Territories): Horizontal injection in vertical, tabular fissures. Canadian Journal of Earth Sciences 23, 827–838.

Banerjee, D., Singhvi, A.K., Pande, K., Gogte, V.D., Chandra, B.P., 1999. Towards a direct dating of fault gouges using luminescence dating techniques—methodological aspects. Current Science 77, 256–269.

Begin, Z.B., Ehrlich, A., Nathan, Y., 1974. Lake Lisan, the Pleistocene precursor of the Dead Sea. Geological Survey of Israel Bulletin 63, (30pp.).

Begin, Z.B., Steinberg, D.M., Ichinose, G.I., Marco, S., 2005. A 40,000 years unchanging seismic regime in the Dead Sea rift. Geology 33, 257–260.

Borradaile, G.J., 1984. A note on sand dyke orientations. Journal of Structural Geology 6, 587–588.

Bøtter-Jensen, L., Bulur, E., Duller, G.A.T., Murray, A.S., 2000. Advances in luminescence instrument systems. Radiation Measurements 32, 523–528.

Diller, J.S., 1890. Sandstone dikes. Geological Society of America Bulletin 1, 411–442.

Duller, G.A.T., Bøtter-Jensen, L., Kohsiek, P., Murray, A.S., 1999. A high sensitivity optically stimulated luminescence scanning system for measurement of single sand-sized grains. Radiation Protection Dosimetry 84, 325–330.

Eyal, Y., 1988. Sandstone dikes as evidence of localized transtention in a transpressive regime, Bir Zreir area, eastern Sinai. Tectonics 7, 1279–1289.

Fukuchi, T., 1992. ESR studies for absolute dating of fault movements. Journal of the Geological Society 149, 265–272.

Galli, P., 2000. New empirical relationships between magnitude and distance for liquefaction. Tectonophysics 324, 169–187.

Garfunkel, Z., 1981. Internal structure of the Dead Sea leaky transform in relation to plate kinematics. Tectonophysics 80, 81–108.

Haase-Schramm, A., Goldstein, S.L., Stein, M., 2004. U–Th dating of Lake Lisan aragonite (Late Pleistocene Dead Sea) and implications for glacial East Mediterranean climate change. Geochimica et Cosmochimica Acta 68, 985–1005.

Ikeya, M., Miki, T., Tanaka, K., 1982. Dating of a fault by electron spin resonance on intrafault material. Science 215, 1392–1393.

Jacobs, Z., Duller, G.A.T., Wintle, A.G., 2003. Optical dating of dune sand from Blombos Cave, South Africa: II—single grain data. Journal of Human Evolution 44, 613–625.

Kaufman, A., 1971. U-series dating of Dead Sea basin carbonates. Geochimica et Cosmochimica Acta 35, 1269–1281.

Ken-Tor, R., Agnon, A., Enzel, Y., Stein, M., Marco, S., Negendank, J.F.W., 2001. High-resolution geological record of historic earthquakes in the Dead Sea basin. Journal of Geophysics Research 106, 2221–2234.

Lee, H.K., Yang, J.S., 2003. ESR dating of the Wangsan fault, South Korea. Quaternary Science Reviews 22, 1339–1343.

Levi, T., Weinberger, R., Aïfa, T., Eyal, Y., Marco, S., 2006. Earthquake-induced clastic dikes detected by anisotropy of magnetic susceptibility. Geology 34, 69–72.

Marco, S., Agnon, A., 1995. Prehistoric earthquake deformation near Masada, Dead Sea graben. Geology 23, 695–698.

Marco, S., Stein, M., Agnon, A., Ron, H., 1996. Long-term earthquake clustering: A 50,000 year paleoseismic record in the Dead Sea graben. Journal of Geophysical Research 101, 6179–6192.

Marco, S., Weinberger, R., Agnon, A., 2002. Radial fractures formed by a salt stock in the Dead Sea Rift, Israel. Terra Nova 14, 288–294.

McCalpin, J.P. (Ed.), 1996. Paleoseismology International Geophysical Series, vol. 62. Academic Press, San Diego, (588pp.).

Migowski, C., Agnon, A., Bookman, R., Negendank, J.F.W., Stein, M., 2004. Recurrence pattern of Holocene earthquakes along the Dead Sea Transform revealed by varve-counting and radiocarbon dating of lacustrine sediments. Earth and Planetary Science Letters 222, 301–314.

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57–73.

Murray, A.S., Wintle, A.G., 2003. The single aliquot regenerative dose protocol: potential for improvements in reliability. Radiation Measurements 37, 377–381.

Obermeier, S.F., 1998. Liquefaction evidence for strong earthquakes of Holocene and latest Pleistocene ages in the states of Indiana and Illinois, USA. Engineering Geology 50, 227–254.

Porat, N., Wintle, A.G., Amit, R., Enzel, Y., 1996. Late Quaternary earthquake chronology from luminescence dating of colluvial and alluvial deposits of the Arava Valley, Israel. Quaternary Research 46, 107–117.

Porat, N., 2002. Analytical procedures in the Luminescence dating laboratory. Geological Survey of Israel Technical Report, TR-GSI/2/2002, 44pp. (in Hebrew).

Tauxe, L., 1998. Paleomagnetic Principles and Practice. Kluwer Academic Publishers, Boston, MA, (299pp.).

Ulusoy, Ü., 2004. ESR dating of North Anatolian (Turkey) and Nojima (Japan) faults. Quaternary Science Reviews 23, 161–174.

Usami, T., Toyoda, S., Mizoguchi, K., Shimamoto, T., Hirose, T., 2005. Decay of ESR signals by high speed friction experiments: implications for ESR dating of fault movements. In: LED 2005—11th International Conference on Luminescence and Electron Spin Resonance Dating, Cologne.

Weinberger, R., Agnon, A., Ron, H., 1997. Paleomagnetic reconstruction of a diapir emplacement: a case study from Sedom diapir, the Dead Sea rift. Journal of Geophysical Research v. 102, 5173–5192.

Zak, I., 1967. The geology of Mount Sedom. Ph.D. thesis, Hebrew University, Jerusalem.