Post-glacial slip history of the Sparta fault (Greece) determined by ^{36}Cl cosmogenic dating: Evidence for non-periodic earthquakes

Lucilla Benedetti,[1] Robert Finkel,[1] Dimitris Papanastassiou,[2] Geoffrey King,[3] Rolando Armijo,[3] Frederick Ryerson,[1] Daniel Farber,[1] and Frederic Flerit[3]

Received 4 December 2001; revised 26 February 2002; accepted 1 March 2002; published 27 April 2002.

[1] Using ^{36}Cl cosmic ray exposure dating we obtained continuous exposure histories for 7–12 m-high limestone surfaces at two sites (10 km apart) on the Sparta normal fault scarp. As each major earthquake adds new surface to the cumulative scarp exposing new material to cosmic-ray bombardment these exposure histories allow the slip history to be constrained. The results show that an earthquake occurred on this fault 2800 ± 300 yr ago. We infer that this is the seismic event that destroyed ancient Sparta in 464 B.C. Four earlier earthquakes ruptured the Sparta fault in the last 13 ka with similar slip amplitudes of about 2 m and with time intervals ranging from 500 yr to 4500 yr. The observations also confirm that the Sparta scarp is post-glacial, supporting the hypothesis that similar scarps elsewhere in the Mediterranean region have a comparable age. The absence of any event since 464 B.C. could suggest a future event is imminent. However, the irregularity of earthquake time intervals could also be due to changes of loading with important consequences for the mechanics of continental deformation. *INDEX TERMS:* 1242 Geodesy and Gravity: Seismic deformations (7205); 1035 Geochemistry: Geochronology; 7221 Seismology: Paleoseismology; 7223 Seismology: Seismic hazard assessment and prediction; 7230 Seismology: Seismicity and seismotectonics

1. Introduction

[2] The Sparta fault is located in the southern Peloponnese and passes less than 5 km west from the city of Sparta. It is part of a major normal fault system, 150 km or more in length, that separates the most easterly part of the Peloponnese from the central part of the peninsula (Figure 1). Near Sparta the fault bounds the eastern front of the Taygetos Mountains (2409 m), (Figure 2a).

[3] The mountain front shows evidence for uplift throughout the Quaternary with triangular facets up to 750-m-high sloping between 20°–40°, wineglass canyons and perched valleys [*Armijo et al.*, 1991], (Figure 2a). At the base of this escarpment, a continuous fresh scarp cuts limestone bedrock and indurated conglomerates. The scarp is nearly continuous with a steepness of 65–68° and well-preserved slickensides (Figure 2b). The maximum height of the scarp is 10–12 metres, progressively decreasing towards the ends. The few local variations are associated with active streams and in these places hangingwall erosion causes the scarp to be locally higher. The regularity of the scarp (see Figure 2a) is powerful evidence that the footwall and hanging-wall surfaces were originally continuous and the scarp surface represents fault slip alone. It also suggests that there was no significant erosion or deposition on the hanging-wall (except near active gullies) since the scarp began to form.

[4] A number of authors have suggested that numerous well-preserved limestone escarpments around the eastern Mediterranean, similar to those in Sparta, are post-glacial in age [*Armijo et al.*, 1992]. The hypothesis is that during the cold and dry climate that prevailed during the last glaciation [*Allen et al.*, 1999; *Peyron et al.*, 1998] the slopes were unstable so that free-faces formed during repeated earthquakes were immediately buried (Figure 3a). Depositional layering in the hanging-wall, considered to be associated with this process, can be seen in many places. At the end of the glaciation, as a consequence of the wet and warm climate, slopes stabilized and earthquake slip began to accumulate and to form the present day cumulative escarpments (Figure 3b). Confirmation of this hypothesis will facilitate regional correlations throughout the Mediterranean region greatly enhancing our ability to assess the rates of Holocene deformation.

[5] Plutarch reports that in 464 B.C. "a greater earthquake than any before reported rent the land of the Lacedomonians into many chasms, shook Taygetos so that sundry peaks were torn away, and demolished the entire city (of Sparta) with the exception of five houses". *Armijo et al.* [1991] suggested that the fault described above was the source of this earthquake. Morphological evidence at the base of the scarp suggests that the last event had a maximum slip of 3 m, consistent with a magnitude of about 7.2 [*Armijo et al.*, 1991].

2. ^{36}Cl Cosmogenic Dating of Limestone Fault Scarps

[6] We have used ^{36}Cl cosmic ray exposure dating to assess the earthquake slip history of the Sparta fault by determining exposure ages as a function of height on the cumulative scarp [cf., *Zreda and Noller*, 1998; *Gran Mitchell et al.*, 2001]. ^{36}Cl is produced primarily through interactions of cosmic ray secondary neutrons and muons with Ca in the scarp limestone ($CaCO_3$), [*Stone et al.*, 1996]. The production rate decreases exponentially with depth and ^{36}Cl is thus mostly accumulated near the surface (Figure 3c). On an active fault scarp, each new earthquake exposes a new section of material. The amount of ^{36}Cl on the scarp is the sum of ^{36}Cl accumulated before the earthquake, at depth, and ^{36}Cl accumulated after the earthquake, when the scarp is exposed above the surface (Figures 3b and 3c). Since the upper parts of the scarp will have been exposed longest they have the highest ^{36}Cl concentrations and concentrations decrease toward the base.

[7] A continuous 20 cm wide sample was collected at two locations separated by 10 km. At Anogia the sample extended the full height of the scarp. At Parori all but the upper 2 meters of the scarp was sampled. The continuous samples were then divided into 10 cm sections for analysis (Figure 2b). The ^{36}Cl and chloride concentration in the carbonate was determined for 82 Parori sub-samples and 64 Anogia sub-samples by isotope dilution accelerator

[1]Lawrence Livermore National Laboratory, Institute of Geophysics and Planetary Sciences, Livermore, USA.
[2]Institute of Geodynamics, National Observatory of Athens, Athens, Greece.
[3]Institut de Physique du Globe de Paris, Laboratoire de Tectonique Paris, France.

0094-8276/02/2001GL014510$05.00

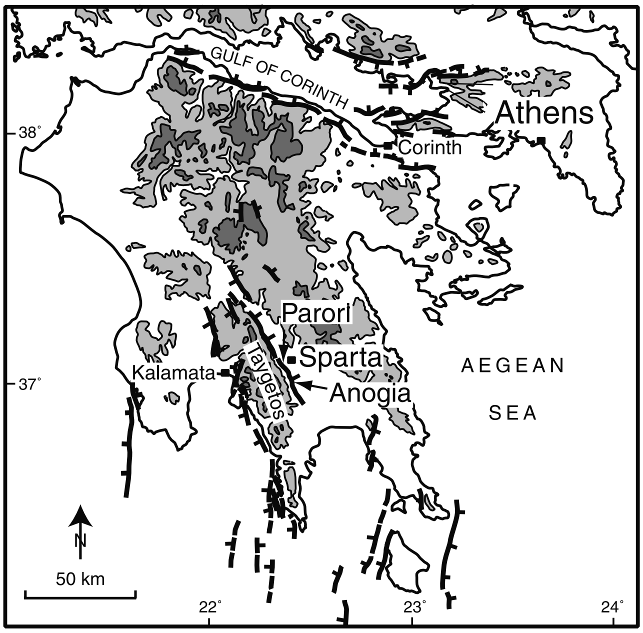

Figure 1. Map of active faults of southern Greece, modified from *Armijo et al.* [1991].

mass spectrometry at the Lawrence Livermore National Laboratory CAMS facility (Figure 4a and supplementary materials).

[8] To assess the seismic history of the fault it is necessary to compare the data to synthetic ^{36}Cl profiles calculated for different earthquake times and slip amplitudes. In these calculations we included all sources of production (energetic neutrons, negative muon capture, capture of secondary neutrons produced by muon capture, fast muon reactions and U/Th fission, [*Stone et al.*, 1998]). We have assumed that no significant erosion or deposition has occurred on the hanging-wall during faulting.

[9] In both profiles four prominent steps in ^{36}Cl concentration can be visually identified (Figure 4a). We asssociated each of these with individual earthquakes. The modelling was carried out separately for the two profiles. The best fit is obtained with 4 events at each site (RMS of 6% and 5% for Parori and Anogia respectively, Figure 4a). Other models with smaller or larger number of events gave similar or higher RMS values. We consider the model presented in figure 4a the best fit as it best satisfies both the ^{36}Cl data, fitting the most prominent discontinuities in the ^{36}Cl distribution, and the morphological observations, yielding the expected value of 2–3 m for the slip of the 464 B.C. earthquake [*Armijo et al.*, 1991].

3. Slip History of the Sparta Fault

[10] Our results give evidence for four events at Anogia at 4.5 ka, 5.9 ka, 8.4 ka and 12.9 ka, and four events at Parori at 2.8 ka, 4 ka, 4.5 ka and 5.9 ka. The 4.5 ka and 5.9 ka events are observed at both sites (Figure 4a).

[11] The age of the most recent earthquake in Parori at 2.8 ± 0.3 ka is consistent with the 464 B.C. date of the destructive Sparta earthquake. This age is obtained using the ^{36}Cl production rate from Ca calculated by *Stone et al.* [1998] for all the various production mechanisms. Other published production rates (*Swanson and Caffee* [2001] and other references there in) are higher than the Stone et al. value and would lead to lower ages.

[12] The most recent and penultimate event (4 ka) are not observed on the Anogia surface, where slip apparently ceased at 4.5 ka. However evidence for small scarps (total offset 2–3 m) cutting the slope can be found 10–20 m below the main Anogia scarp. It is therefore probable that the Sparta earthquake (464 B.C.) and possibly the earlier event bypassed the main scarp at Anogia.

[13] At Parori, the top 2.7 meters of the 10.7 meter-high scarp were weathered and were not sampled. This may explain the absence of the earliest event seen at Anogia (12.9 ka). Moreover, this weathering contrast could be associated with a seismic event. In that case the age of the highest samples taken at Parori, 8.9 ka, might correspond to the 8.4 ka seismic event observed at Anogia. The two ages would differ by only 0.5 ka, within the uncertainty of those model ages ($\sigma \leq 500$ yr).

[14] The form of the upper part of the Anogia profile is flattened. This is the result of cosmogenic nuclide accumulation ‘‘inherited’’ from shallow exposure during the glacial and possibly earlier periods, prior to the exhumation of the measured fault scarp,

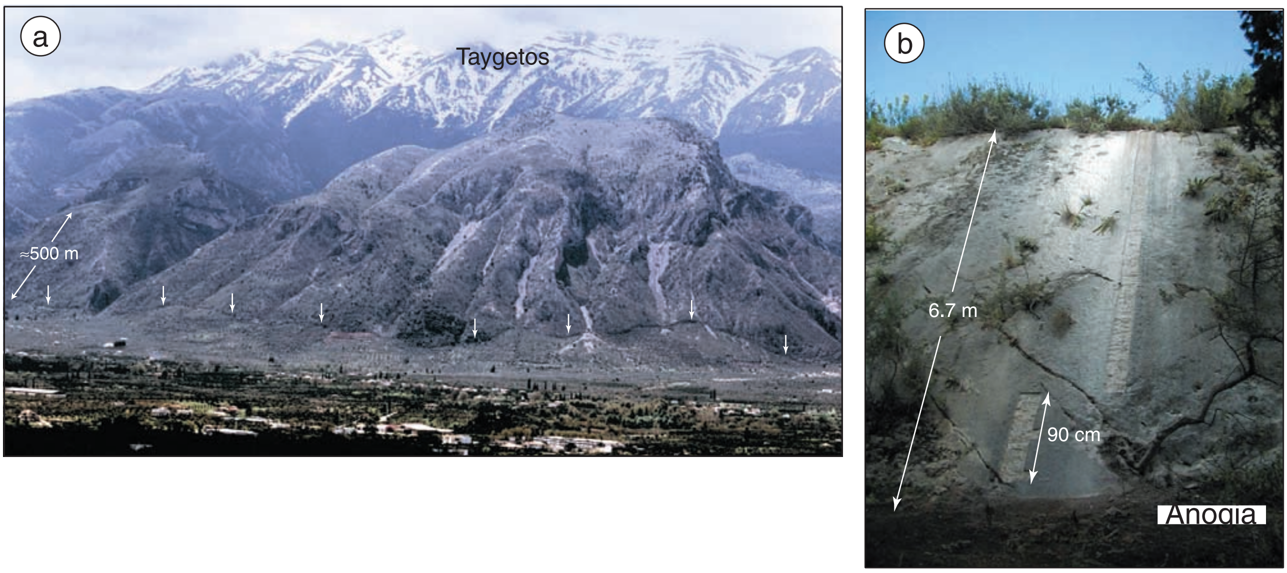

Figure 2. (a) The Sparta fault. The prominent triangular facets in this view are about 500 m high. Arrows outline the scarp trace. Note the regularity of scarp height and the continuity of the scarp along the range front. (b) Photograph of sampling site at Anogia. Samples are 15–20 cm wide, less than 2.5 cm deep. They were divided into 10 cm blocks for measurement.

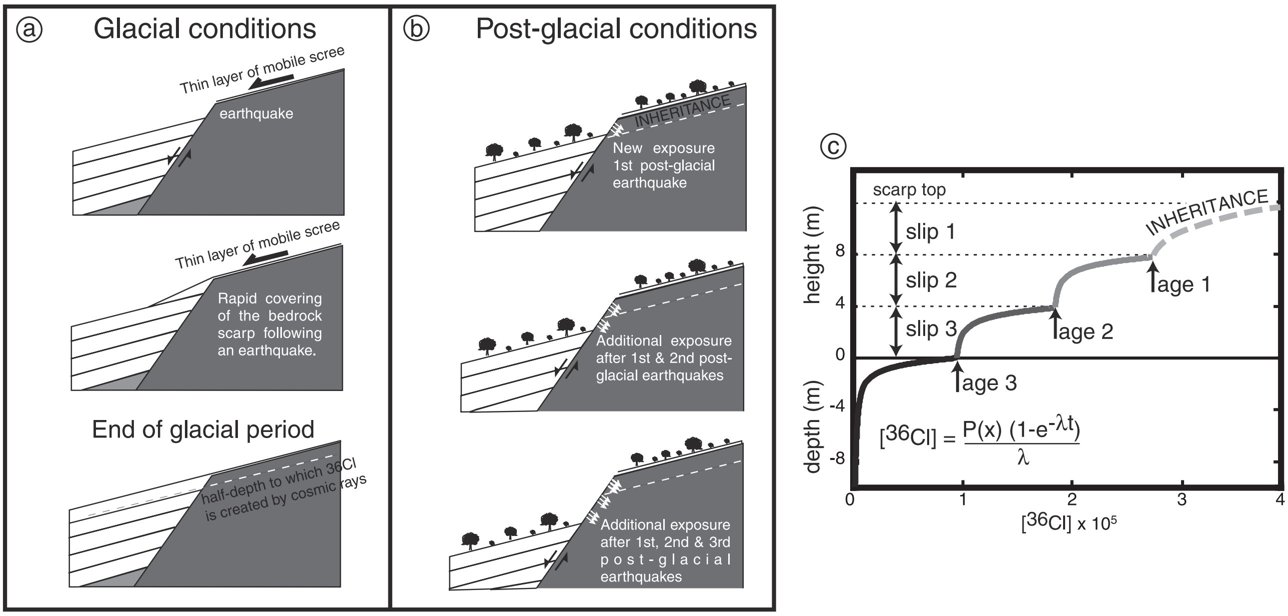

Figure 3. (a) During the cold and dry climate, that prevailed during the last glaciation, slopes were unstable. Free-faces formed during repeated earthquakes were immediately buried. Note layering in the hanging-wall, associated with this process. (b) At the end of glaciation, the wet warm climate stabilized the slopes and earthquake slip began to accumulate and to form the present day escarpments. (c) Synthetic profiles for a scarp created by three earthquakes with 4 m of slip each at 5000 yr intervals. ^{36}Cl concentration is given by the equation with λ the ^{36}Cl decay constant (2.303×10^{-6} yr^{-1}) and P(x) the ^{36}Cl production rate. At sea level and high latitude the ^{36}Cl production rate by fast neutrons is 48.8 ± 3.4 atom/gCa/yr and by muons is 2.1 ± 0.4 atom/gCa/yr [*Stone et al.*, 1996, 1998]. See supplementary materials for additional information.

an effect that has been included in the exposure model (Figure 4a). This "inheritance" is not apparent in the Parori profile since the upper 2.7 m of the scarp is absent.

[15] To illustrate the concordance of the profiles at the two sites, we show in Figure 4b a possible seismic history that includes the missing events at Anogia. The 2.8 ka and 4 ka events (age and slip) are added to the base of Anogia profile, and the 12.9 ka event added to that at Parori (Figure 4b). The inheritance that flattens the top of the Anogia profile has also been accommodated in the Parori model profile. The RMS of these "completed" profiles is the same as that obtained in the previous model (Figure 4).

[16] The slip amplitude for all the events is quite similar with an average slip amplitude from all events equal to 1.9 ± 0.3 m. When considered separately, the slip amplitude of events at Parori (2.1 ± 0.1 m) is slightly larger than that at Anogia (1.7 ± 0.3 m), in agreement with the difference in total scarp height.

4. Discussion and Conclusions

[17] Since the slip of all the events is similar to the 464 B.C. earthquake one, scaling laws for large earthquakes [*Scholz*, 1982; *Wells and Coppersmith*, 1994] suggest that those events ruptured about the same fault length and therefore were about the size of the Sparta earthquake, M ~ 7 [*Armijo et al.*, 1991].

[18] The data show a sequence of earthquakes separated by intervals of 4500 yr, 2500 yr, 1400 yr, 500 yr, and 1200 yr, from the earliest earthquakes to the most recent (Figure 4b inset). The historical record contains no event since the Sparta earthquake in 464 B.C. in agreement with our data. Hence, the minimum recurrence interval between the Sparta earthquake and a future event on this fault is 2500 yr. The four previous recurrence intervals are shorter or equal to the time that has elapsed since the 464 B.C. earthquake. If this recurrence time sequence continues, it might imply that a major event is imminent or overdue. This sequence would also suggest a clustering of events that starts about 5000 yr B.P. On the other hand, the time intervals that we obtained vary between 500 yr and 4500 yr which could suggest that they are random.

[19] What is the slip rate of this fault? Slip accumulated during the last 13 ka yields an integrated slip-rate of about 1 mm/yr. However, if we reduce the observation interval, the slip-rate on the fault seems to have increased with time from 0.5 mm/yr to 2 mm/yr (Figure 4b inset). There may be real temporal variation in the millennial slip rate as opposed to what could be construed as technique-induced bias between geodetic (5–50 yr) and morphochronological (10–100 ka) slip rate determinations. The long-term and short-term slip rates on major continental faults may not always be the same. If so, this has major consequences for the mechanics of continental deformation and for the behaviour of seismogenic faults.

[20] The changes could be the result of variations in the loading rate. Such changes due to either long distance stress interactions between faults or changes of motion on aseismic structures at depth have been previously inferred on the basis of earthquake clustering. For example, over the last 15ka the East Anatolian Fault system has been active when the North Anatolian fault system has been inactive and vice versa [*Ambraseys*, 1989; *Ambraseys and Melville*, 1995]. Major changes of activity have also been proposed along the Dead Sea fault [*Ben-Menahem*, 1991] and in Iran [*Ambraseys and Melville*, 1982]. Recently, paroxysms of activity encompassing the whole of the eastern Mediterranean have been proposed [*Nur and Cline*, 2000]. Doubts about the constancy of loading rates have also been highlighted by differences between geodetic and morphochronological rates for the Kunlun [*Van Der Woerd et al.*, 2000; *Chen et al.*, 2000], Altyn Tagh [*Bendick et al.*, 2000; *Meriaux et al.*, 1998] and Garlock faults [*Peltzer et al.*, 2001].

[21] The observation that the Sparta scarp is post-glacial supports the view that all such similar scarps in the eastern and central Mediterranean are of similar age. These scarps are easily mapped and using the same method that we presented, their slip history can be assessed. This will allow post-glacial deformation rates to be calculated over a wide region with considerable accuracy. When compared with the deformation of the dense GPS networks in the

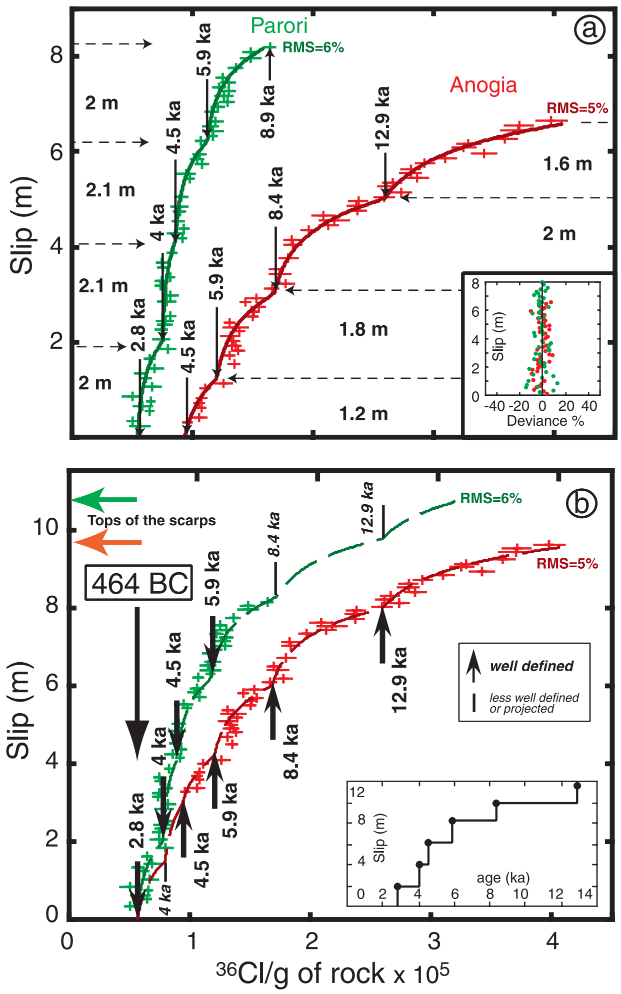

Figure 4. The ^{36}Cl data and the models. Crosses are ^{36}Cl concentrations per gram of rock for each sample with error (7% RMS for Parori and 4% RMS for Anogia, see details in supplementary materials), lines are synthetic profiles. Green indicates Parori, red Anogia. (a) Four earthquakes fit Parori and Anogia with 6% RMS at Parori and 5% RMS at Anogia (see inset with deviance for details). (b) Reconstructed profiles with 2.8 ka and 4 ka events added for Anogia and 12.9 ka event and inheritance added for Parori. Note that events at Parori now fit with the ones at Anogia. The RMS residuals are the same. Inset is time per slip of event deduced from the models.

region [*McClusky et al.*, 2000], this will provide a unique view of the deformation field at different time scales and provide unprecedented information on which to assess seismic risk in this densely populated region. Moreover, for faults such as the Sparta fault, displacement profiles could be taken every 100 meters or even less resulting in detailed slip evolution histories. This could resolve major questions about the mechanics of earthquakes and fault evolution.

[22] **Acknowledgments.** This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No.W-7405-Eng-48. This work has been supported by the program PNRN and "ACI Prevention des Catastrophes Naturelles" of INSU-CNRS contribution 308 and the EC Environment Program (PRESAP). We acknowledge James Dolan and John Stone for thorough reviews that improved the manuscript. We thank Roger Bilham and John Stone for very fruitful discussions. We thank the people at Parori and Sparta. We are thankful to John Southon and Mark Caffee for helping us with the AMS measurement. This is IPGP contribution number 1812 and IGPP contribution UCRL-JC-146922.

[23] Supporting material is available via Web browser or via Anonymous FTP from ftp://kosmos.agu.org, directory "apend" (Username = "anonymous", Password = "guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp/about.html.

References

Allen, J. R., et al., Rapid environmental changes in southern Europe during the last glacial period, *Nature*, *400*, 740–743, 1999.

Ambraseys, N. N., and C. P. Melville, *A history of Persian earthquakes*, Cambridge University Press, Cambridge, 1982.

Ambraseys, N. N., Temporary seismic quiescence: SE Turkey, *Geophys. Jour. Int*, *96*, 311–331, 1989.

Ambraseys, N. N., and C. P. Melville, Historical evidence of faulting in Eastern Anatolia and Northern Syria, *Annali di Geophysica*, *38*, 337–343, 1995.

Armijo, R., H. Lyon-Caen, and D. Papanastassiou, A possible rupture normal-fault rupture for the 464 B. C. Sparta earthquake, *Nature*, *351*, 123–125, 1991.

Armijo, R., H. Lyon-Caen, and D. Papanastassiou, East-west extension and Holocene normal-faults scarps in the Hellenic arc, *Geology*, *20*, 491–494, 1992.

Bendick, R., R. Bilham, J. Freymueller, K. Larson, and G. Yin, Geodetic evidence for a slow slip rate in the Altyn Tagh fault system, *Nature*, *404*, 69–72, 2000.

Ben-Menahem, A., Four thousand years of seismicity along the Dead Sea rift, *J. Geophys. Res.*, *96*, 20,195–20,216, 1991.

Chen, Z., et al., Global positionning system measurements from eastern Tibet and their implications for India/Eurasia intercontinental deformation, *J. Geophys. Res.*, *105*, 16,215–16,227, 2000.

Gran Mitchell, S., A. Matmon, P. R. Bierman, Y. Enzel, M. Caffee, and D. Rizzo, Displacement history of a limestone normal fault scarp, northern Israel, from cosmogenic ^{36}Cl, *J. Geophys. Res.*, *106*, 4247–4264, 2001.

McClusky, S., et al., GPS constraints on plate motion and deformation in the eastern Mediterranean: implication for plate dynamics, *Jour. Geophys. Res.*, *105*, 5695–5719, 2000.

Meriaux, A., et al., Large-scale strain patterns, great earthquakes, and Late Pleistocene slip-rate along the Altyn Tagh fault (China), *Eos (Fall Meet. Suppl.)*, *79*, 400, 1998.

Nur, A., and E. H. Cline, Poseidon's Horses: Plate tectonics and earthquake storms in the late Bronze Age Aegean and Eastern Mediterranean, *Jour. of Archaeological Sci.*, *27*, 43–63, 2000.

Peyron, O., et al., Climatic reconstruction in Europe for 18,000 yr B, *P. from pollen data, Quaternary Reseach*, *49*, 183–196, 1998.

Peltzer, G., F. Crampe, S. Hensley, and P. A. Rosen, Transient strain accumulation and fault interaction in the eastern California shear zone, *Geology*, *29*(11), 975–978, 2001.

Plutarch, *Lives: Cimon*, Harvard University Press, Cambridge, 1961.

Scholz, C. H., Scaling laws for large earthquakes: consequences for physical models, *Bull. Seis. Soc. Am.*, *72*, 1–15, 1982.

Stone, J. O. H., G. L. Allan, L. K. Fifield, and R. G. Cresswell, Cosmogenic chlorine-36 from calcite spallation, *Geochim. Cosmochim. Acta*, *60*, 679–692, 1996.

Stone, J. O. H., J. M. Evans, L. K. Fifield, G. L. Allan, and R. G. Cresswell, Cosmogenic chlorine-36 production in calcite by muons, *Geochim. Cosmochim. Acta*, *62*, 433–454, 1998.

Swanson, T. W., and M. L. Caffee, Determination of ^{36}Cl production rates derived from the well-dated deglaciation surfaces of Whidbey and Fidalgo Islands, Washington, *Quaternary Research*, *56*, 366–382, 2001.

Van Der Woerd, J., et al., Uniform slip-rate along the Kunlun fault: Implications for seismic behaviour and large-scale tectonics, *Geophys. Res. Lett.*, *27*, 2353–2356, 2000.

Wells, D. L., and K. J. Coppersmith, New empirical relationships among magnitude, rupture length, rupture width, rupture area and surface displacement, *Bull. Seism. Soc. Am.*, *84*(4), 974–1002, 1994.

Zreda, M., and J. Noller, Ages of prehistoric earthquakes revealed by cosmogenic chlorine-36 in a bedrock fault scarp at Hebgen Lake, *Science*, *292*, 1097–1099, 1998.

L. Benedetti, R. Finkel, F. Ryerson, and D. Farber, Lawrence Livermore National Laboratory, Institute of Geophysics and Planetary Sciences, Livermore, USA.

D. Papanastassiou, Institute of Geodynamics, National Observatory of Athens, Athens, Greece.

G. King, R. Armijo, and F. Flerit, Institut de Physique du Globe de Paris, Laboratoire de Tectonique Paris, France.