Paul

MEASURING FAULT DISPLACEMENT RATES USING IN-SITU COSMOGENIC ^{36}Cl: THE DISPLACEMENT OF THE NAHEF EAST BEDROCK FAULT SCARP IN NORTHERN ISRAEL

A Thesis Proposal Presented

by

Sara E. Gran

to

The Faculty of the Geology Department

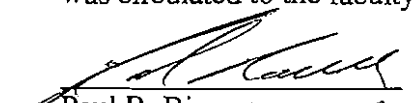
of

The University of Vermont

(March 15, 1998)

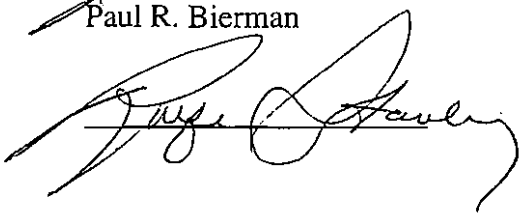
Accepted by the Faculty of the Geology Department, the University of Vermont, in partial fulfillment of the requirements for the degree of Master of Science specializing in Geology.

The following members of the Thesis Committee have read and approved this document before it was circulated to the faculty:



Advisor

Paul R. Bierman



_____

_____

Abstract

My master's thesis will estimate the age and rate of fault motion by measuring concentrations of *in situ*-produced cosmogenic ^{36}Cl from the surface of a 10 m normal fault scarp. The limestone fault scarp chosen for this study is located in the Galilee of northern Israel. Regional extensional activity exposed the scarp at the Earth's surface and cosmic rays began interacting with elements in the limestone, producing otherwise-rare isotopes. Since the cosmogenic reactions occur at a relatively steady rate, by measuring isotopes along an evenly-spaced down-dip profile, I will attempt to determine when successive increments of the scarp were exposed.

I have mapped and sampled the scarp; these samples will be processed to determine isotope concentrations. Mathematical models, based on production rates modified for the surface geometry and rock chemistry, will then be developed in order to translate the isotope concentrations into model exposure ages. There are currently no fault-rate data for this particular fault system, located in the heavily-populated Beit-Hakerem Valley, with which to develop seismic hazard assessments. This scarp also represents the end of landform-creating extensional motion in the Northern Galilee region, so displacement-rate and exposure age estimates will help constrain the timing of the local larger-scale tectonic activity.

Introduction

My master's thesis research addresses a significant and as yet intractable problem in paleoseismology and seismic hazard assessment, dating earthquakes responsible for bedrock fault scarps, and calculating faulting rates for such scarps. Most paleoseismicity studies have focused on faults occurring in unconsolidated sediment where trenchable, fault-related colluvial wedges develop on the down-dropped block and where ^{14}C-dateable material is buried. This trenching method is not applicable where fault scarps are formed entirely in bedrock and no colluvial wedge forms. For this reason, most bedrock scarps remain undated (McCalpin, 1996). The continued development of a new tool capable of providing numerical age estimates for motion on bedrock scarps could significantly supplement the data available for seismic risk assessments. I will address this problem by applying *in situ*-produced cosmogenic isotope dating to a particular limestone fault scarp, the Nahef East Scarp (NES), located in northern Israel (figures 1a and 1b).

The build-up of cosmogenic isotopes over time allows direct numerical dating of the exposure of geomorphic surfaces (Bierman, 1994). As rock faults, and previously-subsurface material is uncovered, cosmic ray bombardment will produce a distinctive set of otherwise-rare isotopes inside the mineral lattices; the longer a fault surface is exposed, the higher the isotope concentration will be. Fast cosmic ray nucleons striking the calcium-rich limestone cause the reaction $^{40}Ca(2n, 3p)^{36}Cl$ (Lal, 1988). The ^{36}Cl concentrations on the fault scarp may indicate the

timing and number of slip events (or, in the very least, a slip rate), as long as the method provides adequate age resolution and assuming the scarp was exposed due to fault motion and has not undergone a long period of burial.

Impact of the project

This study could have a significant impact in the fields of paleoseismology, earthquake hazard assessment, and landform evolution. My project will test a new tool for unraveling earthquake and displacement histories in various parts of the world where ^{14}C dating or trenching are not effective methods, and may serve as a check for previous seismic estimates which utilized these other dating methods. It will also help quantify the earthquake risk of this heavily-populated region of the Middle East. My estimate for the development of the Nahef East scarp will help define the long-term tectono-geomorphic history of this little-understood area.

Geologic Setting

The Nahef East scarp is one of a series of E-W trending normal fault scarps in the Galilee of northern Israel; specifically, it is the scarp that forms the bottom of the northern escarpment of the Beit-Hakerem Valley (figure 1b). This region is a basin and range-style extensional zone west of and associated with the Dead Sea Transform Fault (Freund, 1970). The upper fault block in my study site consists of a Turonian limestone, and the lower block is younger Senonian chalk (Michelson et al., 1987). The fault scarp represents only the last 5-10 meters of displacement in a tectonic history that has offset these two units as much as 300 meters.

Although this 5-10 meter-high scarp is planar and has a fresh-looking surface, it has no established historic or paleo-earthquake record from the past 3000 years, implying that the latest major seismic activity occurred at least 3000 years ago (Ben-Menahem, 1991). Recurrence interval and slip displacement rate estimates on this fault will be useful in determining the seismic risk for this populated and earthquake-prone area and understanding its tectonic evolution (Matmon, 1997; Rotstein, 1987; Shapira and Feldman, 1987).

Limitations of the Method

There are several assumptions and limitations involved with dating earthquakes and determining rates of fault motion using cosmogenic isotopes. Is ^{36}Cl produced at a fast enough

rate in this limestone for me to be able to distinguish between exposure ages which might be only several hundreds or thousands of years apart? The accepted production rate (scaled to sea-level, high latitude) is about 50 atoms/(g Ca yr.) (Stone, 1996). This corresponds to about 4 x 10^5 atoms of ^{36}Cl being produced in 20 grams of limestone per thousand years. I will need to be sure my analytical method is precise enough to reliably distinguish between exposures occurring at least every thousand years.

This study assumes that the NES was exposed due to tectonic activity instead of erosion, and was not buried by sediment for any great length of time. If the scarp were exposed by erosion, then my ^{36}Cl ages will indicate a stripping rate instead of faulting rate. If the scarp were buried during or after faulting, modeling an exposure age becomes very difficult. It is impossible to establish with certainty that these situations did not occur, though preliminary field observations, such as fault geometry and preservation of primary features, as well as lack of any current scarp burial by colluvium, support a tectonic origin for the scarp.

Related Research

Previous cosmogenic isotope studies include discussions on the fundamental nuclear physics involved with isotope production (Bard, 1997; Lal, 1988) and production rates (Zreda et al., 1991; Nishiizumi et al., 1991). Other investigators have concentrated on determining the ages of bedrock surfaces (Kurz et al., 1994; Zreda et al., 1991; Nishiizumi et al., 1991); glacial landforms such as moraines and striated bedrock (Larsen, 1995; Brown, et al., 1991; Bierman et al., in review); and wave-cut ocean terraces (Stone et al., 1996). Herut et al. (1992) and Andrews et al. (1986) discuss the abundance of ^{36}Cl in the environment and the different ways it is produced. *In situ* cosmogenic ^{36}Cl production rates and analytical methods for concentration measurements are discussed in Stone, 1996; Bierman et al., 1995; Dep et al., 1994; Leavy et al., 1987; and Stone et al., 1994. Several researchers have applied specifically ^{36}Cl dating to attain exposure ages and erosion rates (Dep et al., 1996; Dockhorn et al., 1991; Liu et al., 1994; Stone, 1994). There is an abstract (Zreda, 1995) that considers the possibility of measuring faulting rates by measuring cosmogenic isotopes from a bedrock fault scarp. It is, however, a preliminary study and has not been presented as a formal publication.

The tectonics of Israel, especially the Dead Sea Transform (DST), has been extensively studied in terms of plate motion and seismicity (Rotstein, 1987; Shapira and Feldman, 1987; Ben-Menahem, 1991; Enzel, 1994). The DST is an active left-lateral strike-slip fault extending northward from the Red Sea (figure 1a). The region containing the Nahef East scarp, about 30 km to the west of the DST, is currently being mapped in detail and is part of a region-wide study of the tectonic geomorphology of the Galilee region (Matmon, 1997). There are no specific references to the seismic history of the NES.

Research plan/methods

This project is composed of three distinct but interrelated components; field mapping and sample collection (completed winter 1997-98), laboratory chemical analysis, and computer modeling.

Mapping and Sample Collection. A 1-kilometer section of the extensive series of en echelon fault scarps was mapped and profiled using a Trimble 4400 Real Time Kinematic Global Positioning System, with horizontal and vertical precision errors of < 3 cm (figure 2). The profiles (cross-sections), oriented perpendicular to the fault surface, will be used to calculate total vertical displacements (figure 3a).

I chose the location for ^{36}Cl sample collection during this mapping phase. The selected scarp surface was planar and relatively fresh, indicating that little erosion had taken place. Erosion of a surface makes exposure age determination complicated and more uncertain. The location was also selected in order to detect as many faulting events as possible. At the sample location the scarp is 10 meters high (measured down-dip), nearly the highest displacement of the entire scarp (figures 2 and 3).

The samples were taken with a paleo-magnetic rock-coring drill every 30 centimeters along a single down-dip profile. I sampled 9.6 meters of the scarp, including three samples from below the current scarp base (35 samples). At two heights, I took a second set of samples to serve as an accuracy check. A large sample from the upper surface of the scarp was also taken, resulting in a total of 38 samples (figure 3b).

Chemical Analysis. I am currently processing the samples at the University of Vermont, according to the method of Stone et al. (1996) (for full procedure, see Appendix 1). The rock cores have been trimmed of their weathered surfaces to remove meteoric ^{36}Cl, and have been measured, weighed, and crushed. The crushed limestone was sieved to separate the 250-500 micron fraction. The surfaces of the grains of this fraction will be etched with HNO_3 to remove any remaining meteoric ^{36}Cl, rinsed thoroughly in deionized water, then completely dissolved in weak HNO_3. I will take aliquots of each dissolved sample to measure major and minor element abundances, using the ICP at the Plant and Soil Science Department at UVM and the ICP-MS at Dartmouth University, respectively. The major and minor element abundances are necessary in order to determine the target chemistry of the rock, which affects the rate of ^{36}Cl produced by cosmic ray bombardment. Total chloride in the rock will be measured both with absorption spectrophotometry and isotope dilution.

The chlorine will be separated and purified (as AgCl) using standard techniques (Stone, 1997; Bierman, 1995; Zreda, 1991). Prepared targets of AgCl will be taken to Livermore National Laboratory where I will measure the $^{36}Cl/Cl$ ratios, using accelerator mass spectrometry (AMS). The whole rock chemistry and measured isotope ratios will be used to determine the concentration of ^{36}Cl in each sample and, in conjunction with production rate corrections made for fault scarp location, geometry and shielding, a model exposure age for each sample elevation.

Modeling. Because the displacement history of this fault is entirely unknown, I will develop an interpretive model that is consistent with the measured ^{36}Cl abundances. Considering the geometry of the scarp profile obtained from detailed mapping, the measured isotope concentrations, and established isotope production rates for ^{36}Cl (Stone et al., 1996; Zreda, 1991), I will examine mathematically a variety of possible faulting scenarios and select the one that best fits the observed data. Pre-displacement exposure, burial and scarp geometry will have a major effect on final isotope abundances, as well as magnitudes of and time between displacement events. I will need to produce a model that can be programmed to accommodate these variables. Once my model is developed, other scientists working on similar problems will be able to use and modify it to accommodate their own research (see Appendix 2 for my preliminary model).

Possible Outcomes and Interpretations

My master's thesis has several possible outcomes. By plotting sample position vs. isotope concentration I should be able determine the character of fault motion, provided the ^{36}Cl technique is sensitive enough. One possibility is that I may be able to detect individual displacement events by seeing distinct steps in the plotted data, indicating fault motion. Alternatively, the isotope abundances may suggest that the scarp was created with a single slip event. This would be quite interesting, because empirical relationships suggest that a 7.5 magnitude earthquake is necessary in order to produce a 10 meter displacement (McCalpin, 1996). A third possibility is that for a period of time the fault slipped only a little bit at a time (less than my sampling interval of 30 cm). In this situation, the height vs. isotope concentration curve should be smooth. There are an endless number of combinations of displacement magnitudes and ages, but my preliminary models indicate that I should be able to distinguish between the above scenarios (figure 4). Since there are many possible "pathways" to reach the isotope concentrations measured on the scarp, it may be difficult to determine a single, most-likely faulting scenario. In this situation, despite not being able to determine when individual earthquakes occurred, I should still be able to estimate when faulting started and finished and calculate an average displacement rate.

Schedule for Completion

Winter 1997-8 Completed mapping and sampling. *Spring and summer 1998* Defend proposal, process samples, collect accelerator, ICP, ICP-MS and spectrophotometry data. *Fall 1998* Develop models for age determination, present Progress Report, present preliminary findings at GSA national conference in Toronto. *Winter 1998-9* Write. *Spring and Summer 1999* Finish writing. *Fall 1999* Defend Thesis

Funding

I have several funding sources for this project. My living and travel expenses during field work in Israel were paid for by Israeli collaborators at Hebrew University. Airfare to Tel Aviv was provided by the UVM provost's office through an International Educational Incentive Grant. I have support from Israeli and Lawerence Livermore collaborators, as well as a UVM SUGR/FAME research grant, for travel, sample processing, and AMS analyses.

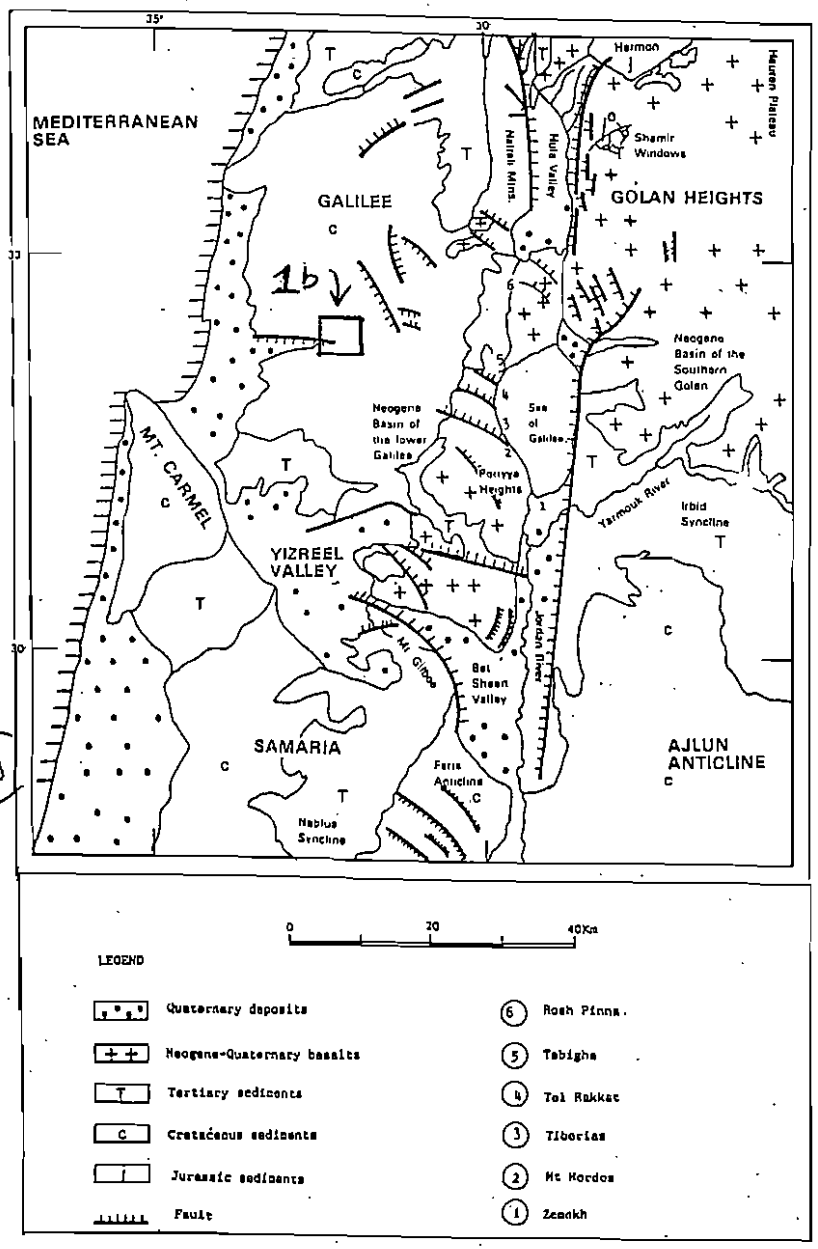


Figure 1a. Structural map of northern Israel (after Michelson, et al., 1987). Field area consists of Cretaceous sedimentary rocks. Many more, smaller normal faults exist in the area than are shown on this map.

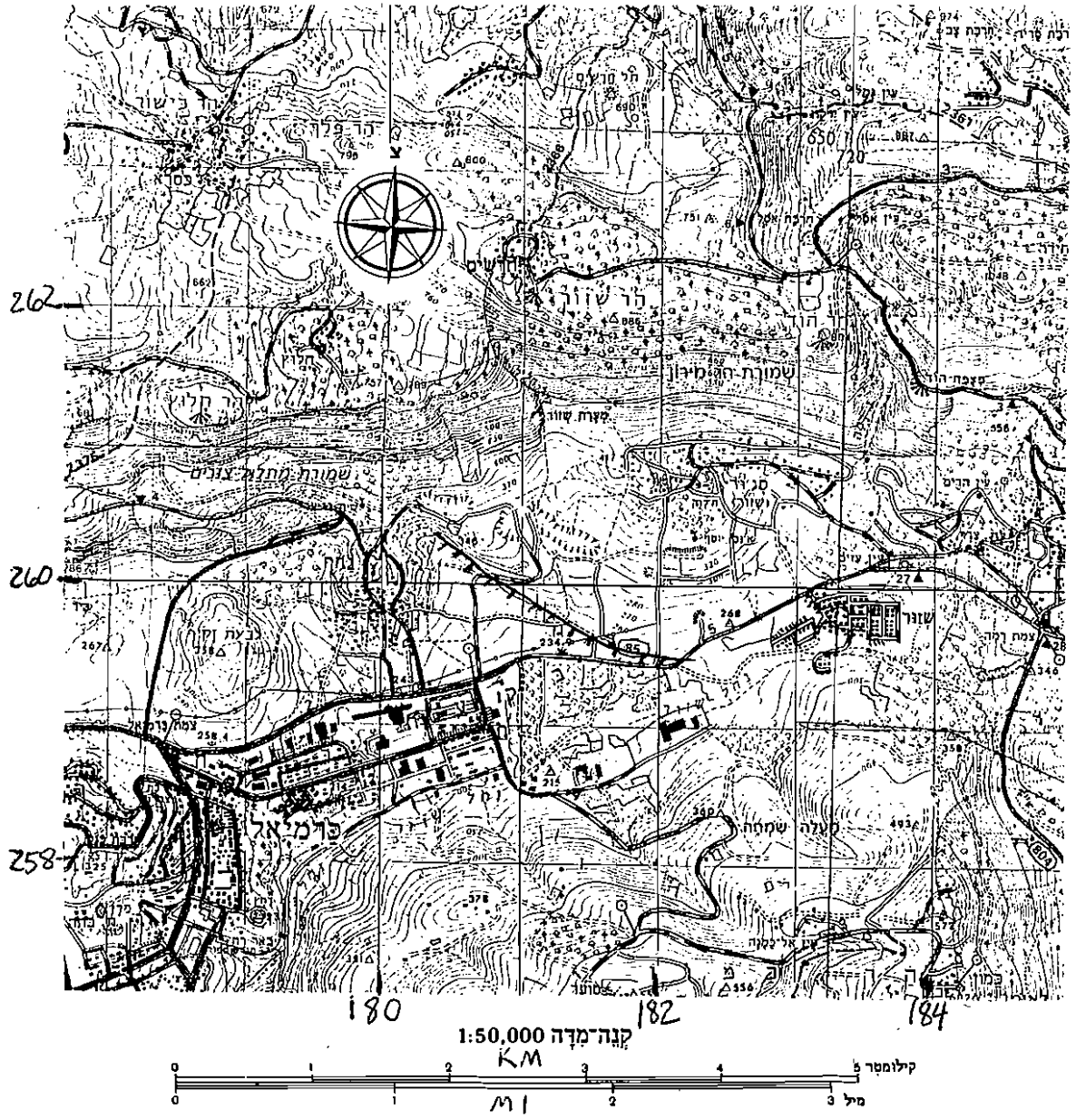


Figure 1b. Topographic map of field area. Nahef East Scarp is shown as a heavy dashed line in the center of the figure. (after Society for the Protection of Nature in Israel, 1:50,000 map series)

Figure 2a plan-view of profile sections + scarp extent

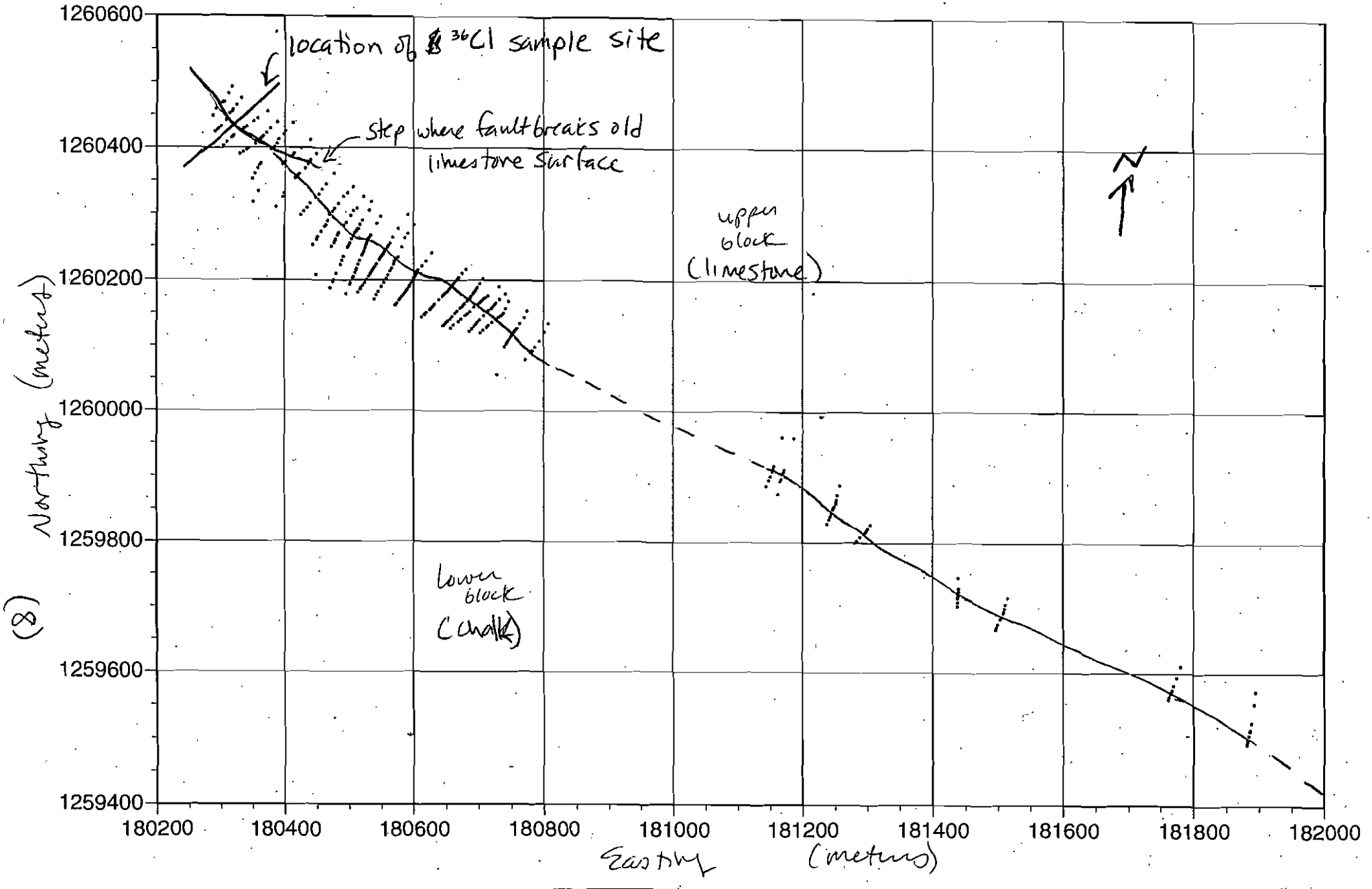


Figure 2. Plan view of fault scarp and profile sections. Profiles were measured with a Trimble 4400 RTK GPS. Eventually, this map will include vertical displacements at each profile, calculated as shown in figure 3a.

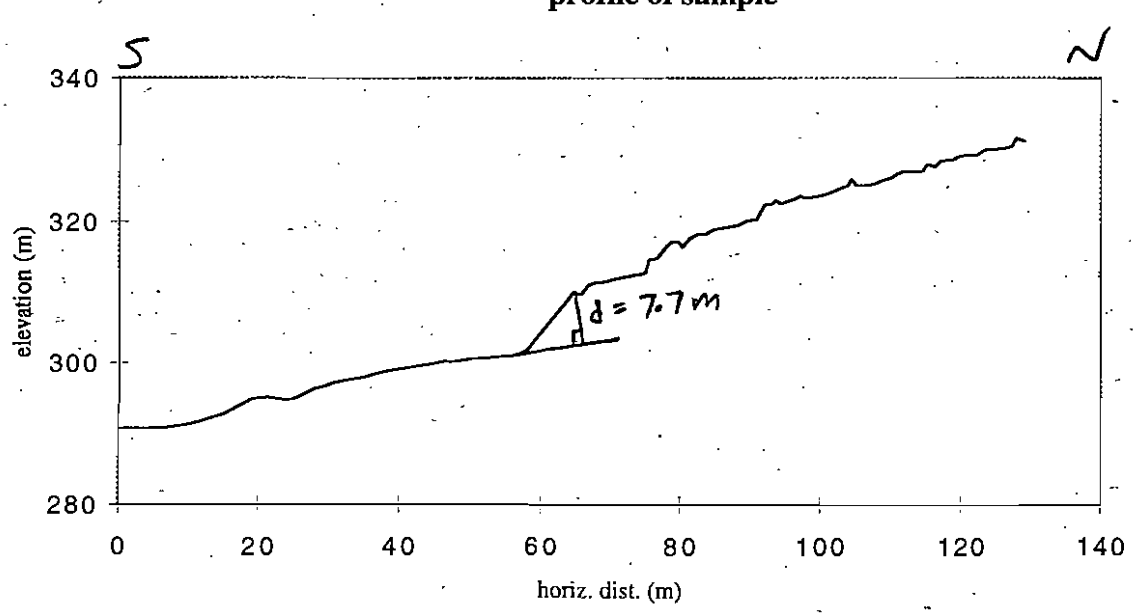


Figure 3a. Cross-sectional profile of sample locality. Total vertical displacement is calculated by extrapolating the lower block surface and measuring the vertical distance perpendicular to the lower block. In this location, the measured scarp height is 10.85 m and the vertical displacement is 7.7 m. Note the increased roughness of the upper block, this is due to karst weathering of the limestone.

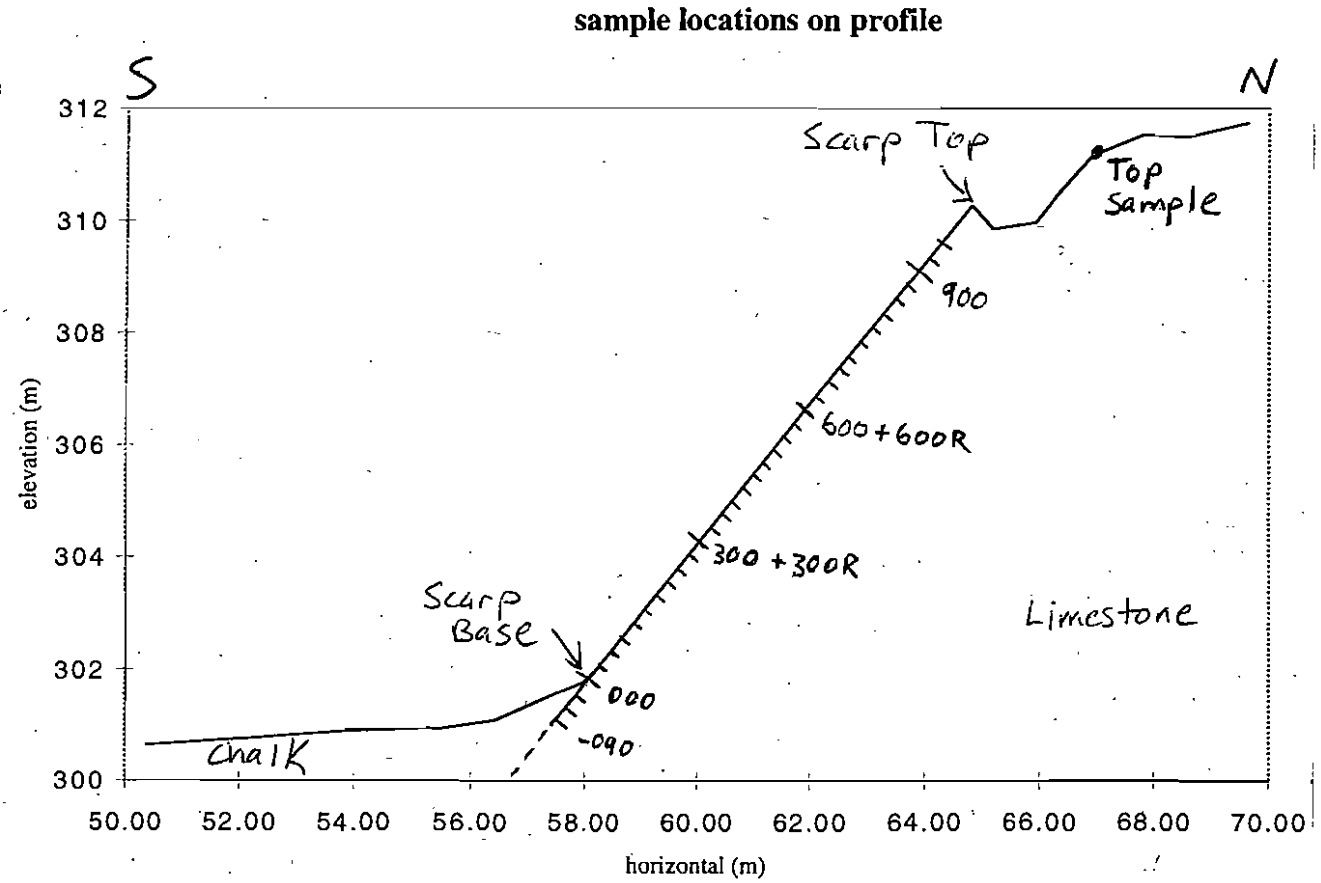


Figure 3b. Close up of sample profile showing locations of all samples. Samples were taken at 30 cm downdip intervals. 3 samples were taken from below the scarp base, and one from the upper surface. At 3 m and 6 m above the base, I took replicate samples. No samples were taken from the upper 1 m of scarp because it was highly weathered.

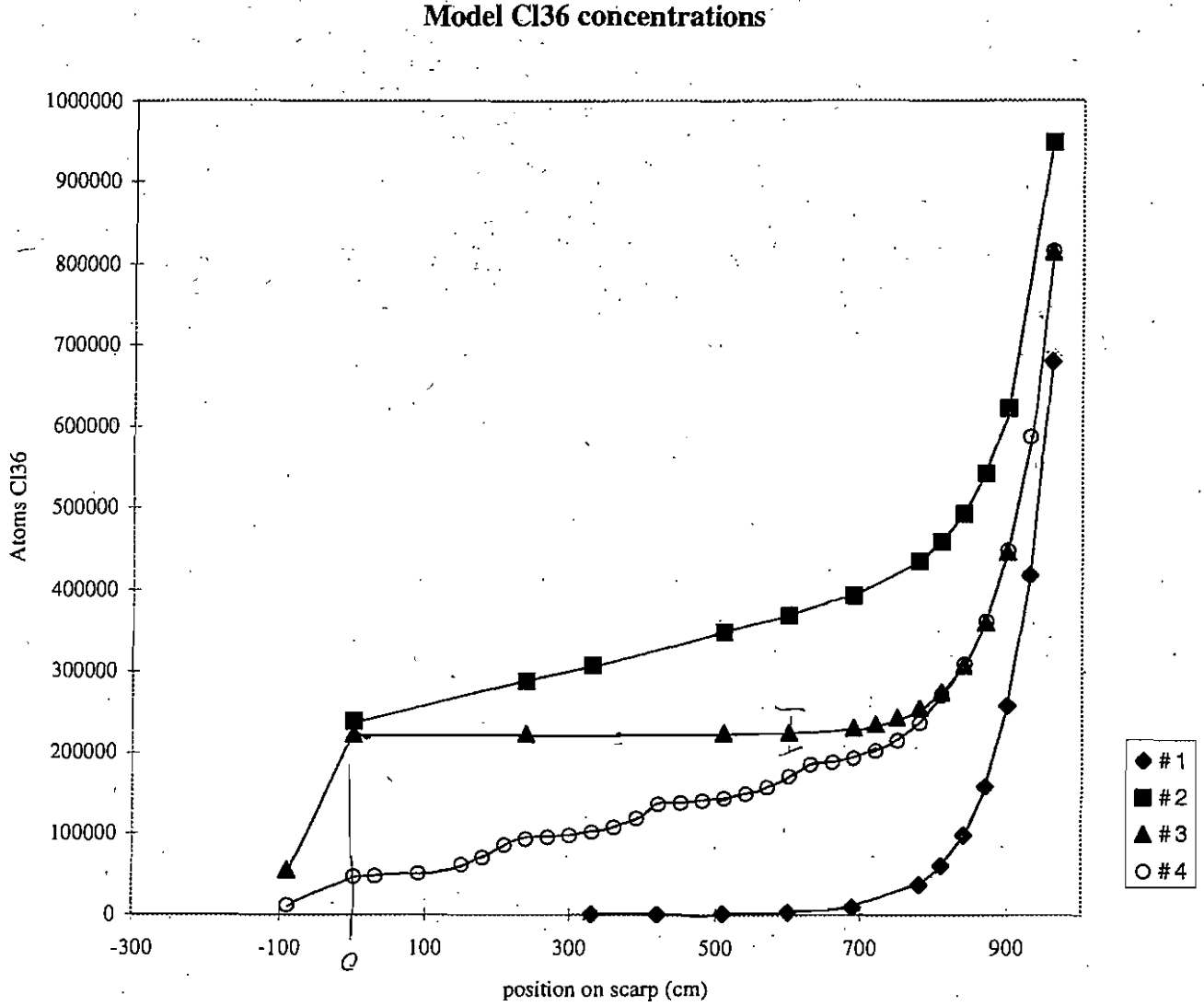


Figure 4. Hypothetical ^{36}Cl concentrations from different faulting scenarios. See Appendix 2 for model mechanics. These models are for the development of a *vertical* scarp (a vertical scarp is simpler to model). For each scenario, exposure starts at 100 Ka. This model ignores isotopic decay. Series #1 (diamonds) represent isotope accumulation if the scarp moved all 10 meters the day before I sampled (all dosing received from upper, unfaulted surface). #2 (squares) is if there was constant creep from 50 Ka-25 Ka. #3 (triangles) is if there was a single fault motion at 25 Ka. #4 (open circles) is if there were a series of 5 two-meter displacements occurring between 25 Ka and the present. The ^{36}Cl in the uppermost sample (on the far right of each line) is proportional to when the scarp first developed. In #1, the top sample was essentially never exposed, and therefore has the smallest amount of ^{36}Cl. #3 and #4 both represent faulting that started 25 Ka. #2 has the highest ^{36}Cl, because in that situation faulting started the earliest, at 50 Ka. Note that the slope of #2 and #4 are parallel, except that #4 represents discrete fault motions. The slope of that line is proportional to long-term displacement rates.

References Cited

Andrews, J. N., J. Ch. Fontes, J. L. Michelot, and D. Elmore (1986). "In-situ neutron flux, ^{36}Cl production and groundwater evolution in crystalline rocks at Stripa, Sweden." Earth and Planetary Science Letters **77**: 49-58.

Bard, E. (1997). "Nuclide production by cosmic rays during the last ice age." Science **277**: 532-533.

Ben-Menahem, A. (1991). "Four Thousand Years of Seismicity Along the Dead Sea Rift." Journal of Geophysical Research **96** no. B12: 195-120.

Bierman, Paul, A. Gillespie, et. al (1995). "Estimating erosion rates and exposure ages with ^{36}Cl produced by neutron activation." Geochimica et Cosmochimica Acta **59**: 3779-3798.

Bierman, Paul R. (1994). "Using in situ cosmogenic isotopes to estimate rates of landscape evolution: A review from the geomorphic perspective." Journal of Geophysical Research **99** (B-7): 13885-13896.

Brown, E. T., J. M. Edmond, G. M. Raisbeck, F. Yiou, M. D. Kurz, and E. J. Brook, (1991). "Examination of surface exposure ages of Antarctic moraines using in situ produced ^{10}Be and ^{26}Al." Geochimica et Cosmochimica Acta **55**: 2269-2283.

Dep, L., D. Elmore, J. Fabryka-Martin, J. Masarik, and R.C. Reedy (1994). "Production rate systematics of in-situ-produced cosmogenic nuclides in terrestrial rocks: monte carlo approach of investigating $^{35}Cl(n,\gamma)^{36}Cl$." Nuclear Instruments and Methods in Physics Research **B92**: 321-325.

Dep, L, D. Elmore, S. Vogt, P. Sharma, M. Bourgeous, and A. Dunne (1996). "Erosion-corrected ages of quaternary geomorphic events using cosmogenic ^{36}Cl in rocks." AMS Prime Lab publication, Purdue University School of Science: 13p.

Enzel, Yehouda, R. Amit, B. Harrison, N. Porat (1994). "Morphologic dating of fault scarps and terrace risers in the southern Arava, Israel; comparison to other age-dating techniques and implications for paleoseismicity." Israel Journal of Earth Sciences **43**: 91-103.

Freund, R. (1970). "The geometry of faulting in the Galilee." Israel Journal of Earth Sciences, **19**: 117-140.

Herut, B., A. Starinsky, A. Katz, M. Paul, E. Boaretto, and D. Berkovits (1992). "^{36}Cl in chloride-rich rainwater, Israel." Earth and Planetary Science Letters **109**: 179-183.

Lal, D. (1988). "In situ-produced cosmogenic isotopes in terrestrial rocks." Annual Reviews of Earth and Planetary Science **16**: 355-388.

Larsen, P. (1995). "In situ production rates of cosmogenic ^{10}Be and ^{26}Al over the past 21.5 Ky. from the terminal moraine of the Laurentide ice sheet, north-central New Jersey." Unpublished MS thesis, University of Vermont.

Leavy, B.D., F. M. Phillips, D. Elmore, P.W. Kubik, and E. Gladney (1987). "Measurement of cosmogenic $^{36}Cl/Cl$ in young volcanic rocks: an application of accelerator mass spectrometry in geochronology." Nuclear Instruments and Methods in Physics Research **B29**: 246-250.

Liu, B., F.M. Phillips, D. Elmore, P. Sharma (1994). "Depth dependence of soil carbonate accumulation based on cosmogenic ^{36}Cl dating." Geology **22**: 1071-1074.

Matmon, A. (1997-8) Personal communication.

McCalpin, James P. (1996). Paleoseismology. Academic Press: San Diego. 588 p.

Michelson, H. A. Flexer and Z. Erez (1987). "A comparison of the eastern and western sides of the Sea of Galilee and its implication on the tectonics of the northern Jordan Rift Valley." Tectonophysics **141**: 125-134.

Rotstein, Yair (1987). "Gaussian probability estimates for large earthquake occurrence in the Jordan Valley, Dead Sea rift." Tectonophysics **141**: 95-105.

Shapira, Avi and L. Feldman (1987) "Microseismicity of three locations along the Jordan Rift." Tectonophysics **141**: 89-94.

Stone, J.O. (1997). Personal communication.

Stone, J. O., G. L. Allan, et al. (1996). "Cosmogenic chlorine-36 from calcium spallation." Geochimica et Cosmochimica Acta **60**: 679-692.

Stone, J., K. Lambeck, L.K. Fifield, J.M. Evans, and R.G. Cresswell (1996). "Late Glacial age for the Main Rock Platform, western Scotland." Geology **24** (8): 673-676.

Stone, J., G.L. Allan, L.K. Fifield, J.M. Evans, A.R. Chivas (1994). "Limestone erosion measurements with cosmogenic chlorine-36 in calcite - preliminary results from Australia." Nuclear Instruments and Methods in Physics Research v. B 92 p. 311-316.

Zreda, M. G. (1995). "Dating of a late Quaternary bedrock fault scarp using cosmogenic chlorine-36." EOS, Transactions, American Geophysical Union (Supplement 46) **76**: 685.

Zreda, M. G., F. M. Phillips, et al. (1991). "Cosmogenic chlorine-36 production rates in terrestrial rocks." Earth and Planetary Science Letters **105**: 94-109.

Appendix 1
^{36}Cl Sample Processing
(Modified from Stone, 1997)

(1) Sample preparation
Trim cores of weathered surfaces (remove top 0.5 cm)
Measure length, weight of core
Break into 1 cm pieces
Grind in jaw crusher, plate grinder
Sieve, save 125-250 and 250-500 micron fractions
Rinse 250-500 micron fraction in DI water until all fines are washed away
Dry in oven overnight

(2) Leaching (to remove meteoric ^{36}Cl)
Tare and label clean 600 mL beaker
Add 20-25 g dry sample
Wet with about 100 mL MQ water. In separate beaker, mix about 15 mL 2N HNO_3 and 50-100 mL MQ. Pour into rock sample beaker slowly (to avoid foaming). Try to get even dissolution of grain boundaries.
Once reaction has died down, cover and let sit for 12-24 hrs. Swirl occasionally.
Rinse 3-4 times with MQ and repeat leaching procedure
Rinse thoroughly with MQ (at least 5 times) to remove ALL $Ca(NO_3)_2$
Dry overnight. Sample should decrease in weight by about 3 g.

(3) Sample loading
Tare and label a clean 600 mL pyrex beaker
Add ~20 g of sample to beaker, weigh. Use more sample if Cl content is really low.

(4) Dissolution
In fume hood, wet sample to a slurry with MQ and gradually add 10 mL 2N HNO_3 per gram of sample. Avoid foaming (add only 10 mL at a time). It will take about 200 mL acid to dissolve 20 g sample.
Once dissolution is complete, swirl to homogenize and then allow insoluble fraction to settle overnight.
Weigh beaker, trying to avoid stirring up sediment.

(5) Splitting for chloride analysis and carrier spiking
Tare and label a clean 50 mL centrifuge tube.
Tare and label two 15 mL centrifuge tubes to receive spec. aliquots
Tare and label 15 mL centrifuge tube for ICP fraction.
Transfer about 13 mL of solution to the 50 mL tube, weigh.
Divide this fraction between small centrifuge tubes: 4 mL in spec vial 1, 8 mL in spec vial 2. Weigh those tubes and calculate how much is left in 50 mL vial.
Dilute remainder to 40 mL, weigh.
Transfer 1 mL to ICP tube, weigh ICP tube.
Dilute ICP fraction to 10 mL.
Discard remainder of clear solution from 50 mL centrifuge tube.

Weigh carrier bottle
Pipette 2-3 mL carrier into sample beaker (make sure no carrier sticks in pipette).
Re-weigh carrier bottle, calculate amount removed.

(6) Separation from dissolution residue

Let sediment settle (if there is time, let it sit overnight again).
Decant as much supernatant as possible into a clean, labelled 600 mL beaker. Cover with watchglass.
Swirl sample, centrifuge remaining material in the 50 mL tube used earlier.
Rinse and re-suspend sediment, centrifuge again and transfer to beaker.
Rinse several more times, discarding supernatant.
Dry in oven overnight, and re-weigh to determine weight of insoluble fraction.

(7) AgCl and Ag2SO4 precipitation

Place the 600 mL beaker containing clear solution on hotplate (set at ~300-350 °F).
Let sit until actively convecting (2 hrs)
In dim room, add 1 mL 10% $AgNO_3$ solution, it should go cloudy and flecks of AgCl should appear.
Let sit on hotplate for an hour to flocculate. Do not disturb.
Tap to collect flecks in a pile on the base of the beaker. Let cool (and settle) in a dark cupboard overnight.
Decant and discard as much clear solution as possible.
Label a clean 50 mL centrifuge tube, centrifuge remaining solution (discarding supernatant). Be sure to rinse out beaker to assure maximum yield.
AgCl will stick in the point of the tube. Add 5 mL MQ, resuspend, recentrifuge, discard supernatant.

(8) Sulphate clean-up

Dissolve precipitate in 2 mL NH_3 solution. This will take about 5 minutes.
Transfer to 10 mL glass test tube (rinse onces).
Add 1 mL saturated $BaNO_3$ solution, precipitate should form.
Top off tube with MQ, cover with parafilm, and let sit for at least 24 hours (the more the better).
Tap precipitate into base of test tube, centrifuge for 5 minutes.
Using clean pipette, transfer clear solution to 15 mL centrifuge tube. Leave last 2 mL of solution in test tube to avoid transferring the precipitate.

(9) Final AgCl precipitation

Place 15 mL centrifuge tube with dissolved AgCl into clean water bath, place on hotplate set at ~300-350 °F.
In separate beaker, put ~20 mL HNO_3 per sample. Add about 1 mL $AgNO_3$ solution per sample. Place on hot plate.
Allow materials to heat to near boiling (~1hr.).
When hot, add about 10 mL acid/silver mixture to centrifuge tube. Tube will steam and go cloudy.
When done steaming, re-cap, and allow to sit and flocculate for 1 hr.
Transfer to dark cabinet to cool and settle overnight.
Tap AgCl into base of tube, centrifuge and decant supernatant.
Rinse once, resuspend, centrifuge and decant supernatant.
Dry in oven overnight (dry on side so bead of water does not sit on plug of AgCl).
Wrap in tin foil and keep stored out of the light.

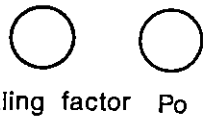
Appendix 2

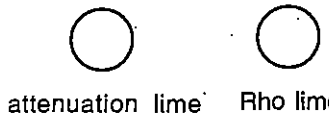
Stella Model for Cl-36 concentrations

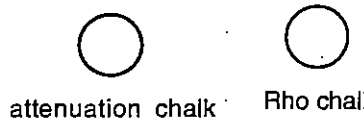
Controls, or factors that remain constant

constants for limestone

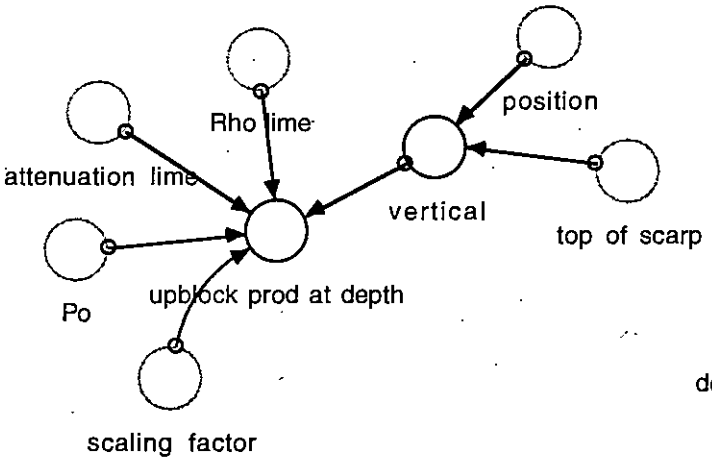
constants for chalk



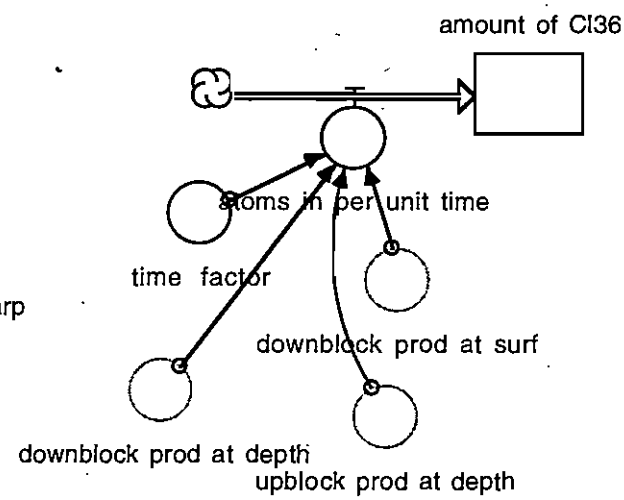




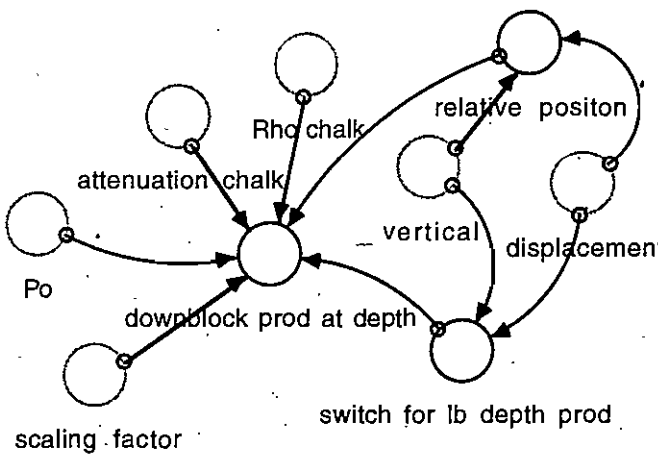
module for 1/2 production received through upper limestone block (always constant regardless of position and displacement)



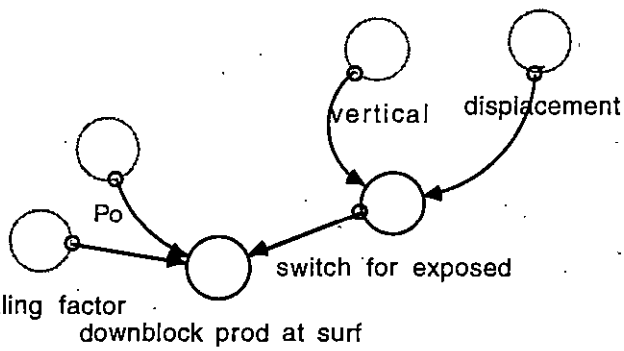
Module for total amount of Cl36 produced for a given sample position, adding all pathways



module for production at depth through lower block (1/2 Po, turns off as soon as position is exposed)



module for production on exposed scarp face (1/2 Po, only turned on after this position is exposed



amount_of_Cl36(t) = amount_of_Cl36(t - dt) + (atoms_in_per_unit_time) * dt
INIT amount_of_Cl36 = 0
INFLOWS:
atoms_in_per_unit_time =
time_factor*(downblock_prod_at_depth+downblock_prod_at_surf+upblock_prod_at_depth)

attenuation_chalk = 160
DOCUMENT: attenuation factor for cosmic rays penetrating to depth in chalk

attenuation_lime = 160
DOCUMENT: attenuation factor for cosmic rays causing reactions at depth

downblock_prod_at_depth =
switch_for_lb_depth_prod*Po*EXP(-relative_positon*Rho_chalk/attenuation_chalk)*scaling_factor

downblock_prod_at_surf = Po*scaling_factor*switch_for_exposed

Po = 18
DOCUMENT: Production rate at surface, corrected for latitude and elevation. This is atoms of Cl36 produced per gram limestone per year

position = 600
DOCUMENT: position of sample (0 is base of scarp, 1020 is top of scarp) in cm

relative_positon = vertical-displacement
DOCUMENT: depth of sample relative to downdropped block (depth through which rays must penetrate)

Rho_chalk = 2.5
DOCUMENT: density of chalk in gm/cm^3

Rho_lime = 2.7
DOCUMENT: density of limestone in gm/cm^3

scaling_factor = 0.5

DOCUMENT: scaling factor accounting for only half production coming from each hemisphere (1/2 from upper block side, 1/2 from down-dropped block side (whether it's surface or at depth)

switch_for_exposed = IF(vertical-displacement<=0)THEN(1)ELSE(0)
DOCUMENT: switch to turn on this exposure when this position becomes uncovered

switch_for_lb_depth_prod = IF(vertical-displacement>0)THEN(1)ELSE(0)
DOCUMENT: switch to turn off at-depth production through down-dropped side when sample position becomes exposed at the surface (then the downblock prod at surface gets turned on). Only one of these will be on at a given time

time_factor = 100

top_of_scarp = 1020
DOCUMENT: Height of scarp in meters

upblock_prod_at_depth = scaling_factor*(Po*EXP(-((vertical*Rho_lime)/attenuation_lime)))

vertical = top_of_scarp-position
DOCUMENT: vertical distance from top of scarp to this sample position