ESTIMATING NORMAL FAULT DISPLACEMENT RATES IN NORTHERN ISRAEL, USING COSMOGENIC ^{36}CL

A Thesis Progress Report Presented

by

Sara E. Gran

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

________________ Advisor

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Introduction

Cosmogenic isotopes are becoming an extremely useful tool in the field of geomorphology. Minute abundances of unstable cosmogenic isotopes (^{10}Be, ^{26}Al, ^{36}Cl), produced via reactions with cosmic rays in surficial rocks, can now be measured using accelerator mass spectrometry (Elmore and Phillips, 1987). By knowing parameters associated with isotope production, including production rates on the surface and at depth, rock chemistry, altitude and latitude of exposure, and different isotope production pathways, these abundances can be incorporated into models which can calculate model ages or erosion rates of numerous types of geomorphic surfaces (e.g. Stone et al., 1998; Stone et al., 1996; Gillespie and Bierman, 1995; Bierman et al., 1995; Bierman, 1994; Stone et al., 1994; Dockhorn et al., 1991). For example, it is possible to calculate displacement rates and possibly the date of motion on a normal fault which causes surficial exposure of a bedrock scarp during displacement events.

I am attempting to unravel, using ^{36}Cl, the displacement history on a bedrock fault scarp located in an extensional zone west of the Dead Sea Transform Fault, northern Israel. The Nahef East normal fault exposes a 2 km-long, 1.5 to 10.5 meter-high scarp of slightly dolomitic limestone (figure 1). The limestone is now placed against much younger chalk and the total displacement of the fault represents hundreds of meters of vertical displacement. The current scarp represents only 2 to 10 meters of displacement, and it is these last few meters of a very long displacement history that I will try to unravel (figure 2).

Concise summary of work conducted to date

I have divided my thesis into 3 components: mapping/sampling, chemical analyses, and numerical modeling.

Mapping. In December/January, 1997-1998 I completed mapping and sampling. Using a high-precision global positioning system, I mapped the scarp extent, thirty scarp transects, and much of the topography of both the upper and lower blocks near the fault (particularly, in the vicinity of the sampled transect). I used these data to construct a topographic map showing the scarp and the transects crossing the scarp (figure 1). I was planning to relate displacement magnitudes to earthquake intensity, however the scarp height is widely variable and does not seem to show the classic relationship of greater vertical displacement at the center of the scarp, tapering to zero at the ends (figure 3). In fact, figure 3 indicates that I have only mapped the eastern portion of the scarp. If this is the case, the western portion of the scarp is underneath the town of Nahef.

Sampling. I collected 40 samples using a rock coring drill from a 10 meter high section of the fault scarp. The samples were collected at 30 cm down-dip intervals. A total of about 150 grams of rock were collected for each sample. The rock samples were labeled and brought back to UVM for chemical analysis.

Chemistry. I am doing two types of chemical analyses. First, I am determining the concentration of ^{36}Cl in each sample, using accelerator mass-spectrometry (AMS). Protocol for preparation of samples for AMS analyses are in Appendix 1 of my thesis proposal. AMS data are a ratio between ^{36}Cl and total rock Cl, not an absolute concentration of ^{36}Cl in the rock. To translate the $^{36}Cl/Cl$ ratio into a concentration of ^{36}Cl, I need to measure the concentration of Cl in each sample. The ratio of $^{36}Cl/Cl$ multiplied by the number of atoms originally in the sample is the number of ^{36}Cl atoms (figure 4). All samples have been prepared for both analyses, and I have AMS data for 18 samples and am working on developing the Cl analysis method with Jennifer Larsen and Don Ross of the Plant and Soil Science department (Florence and Farrar, 1971). I plan on completing the Cl analysis shortly and personally performing the remaining AMS analyses at Lawrence Livermore National Laboratory in November or December, 1998.

The second set of analyses parameterize production rate equations for my specific samples. There are several reactions that produce ^{36}Cl in limestone: Ca-spallation, muon capture by calcium, and thermal neutron capture by ^{35}Cl, for which there are several different neutron production mechanisms, including spallation, muon capture and radiogenic reactions. Each of these reactions have different production rates that depend on major and trace element abundances as well as depth of shielding (Stone, et al, 1998; Bierman et al., 1995).

In order to parameterize ^{36}Cl production rates, I need to know the concentration of: Ca, Mg, O, C, Cl, U, Th, B, Gd, and Sm (Stone et al, 1998). I will measure Ca and Mg concentrations in two different dilutions using the inductively coupled plasma (ICP) spectrometer in the Plant and Soil Science department. I will calculate O and C from the stoichiometric relationships with Ca and Mg. I will measure Cl using the mercury thiocyanite colormetric method (Florence and Farrar, 1971). The remaining elements: U, Th, B, Gd, and Sm will be measured at Dartmouth College using an inductively coupled plasma mass spectrometer (ICP-MS).

Numerical Model. Using chemical and isotope data, scarp geometry, and production at depth equations (Stone, 1998; Fabryka-Martin, 1988), I am developing a model that will allow calculation of fault displacement rates. My preliminary model, programmed in STELLA 3.0, incorporates only the Ca-spallation production rate pathway. I am currently learning how to use a more powerful numerical modeling program, MATLAB. I will program MATLAB to include the following parameters: shielding depth, elemental composition of each sample, sample core size, angle of the scarp, altitude and latitude of the sample site, and the erosion rate of the upper fault surface. By programming each of the different ^{36}Cl production pathways and their relationship with depth, and the measured ^{36}Cl (corrected for the amount of "inherited" ^{36}Cl, which is in steady-state equilibrium with the long-term erosion rate of the upper surface, production rate, and decay rate of ^{36}Cl), I will have the model iteratively solve for a displacement scenario that results in the best fit to the measured amount of ^{36}Cl in all 40 samples.

This model (along with completing the chemical data collection) will be my main focus in the coming months. I currently have a good understanding of the depth-dependence of each ^{36}Cl production pathway and can calculate total ^{36}Cl production rates for different depths (Stone, 1998; Fabryka-Martin, 1988). The next step is to create a dynamic model that will allow me to see what the total ^{36}Cl content of my samples would be for various displacement histories and erosion rates. The final step will be to program the model to iterate through many different displacement histories and match the resulting ^{36}Cl concentrations to those in my actual samples.

A final aspect of my model, which I still need to understand better, is the effect a tilted fault surface has on neutron and muon fluxes. I currently have an equation from John Stone (unpublished) that describes the relationship between a surface tilt and the fast neutron flux. I need to figure out if this equation is correct, and to learn how I can modify it to apply to the thermal neutron and muon fluxes.

Initial interpretations of data collected

I have made some (very) preliminary interpretations with my STELLA model. Using ^{36}Cl and Ca data from six samples (and assuming a Cl content of 40 ppm, real values will likely range from 5-100 ppm, Stone 1998), geometrically correcting for the tilt angle, assuming there are no inherited ^{36}Cl atoms at the beginning of a 100,000 year exposure history, and considering *only* the Ca-spallation reaction, I have calculated that the displacement rate of the scarp is 0.05 cm/yr and fault motion ended approximately 2400 years ago. These numbers were calculated by modeling a variety of displacement histories, each beginning 100,000 years ago, and then observing the shapes of the [^{36}Cl] vs depth graph (figure 5a). The lower portion of the graph (that represents the samples beneath the "surface effect") has a slope that is directly proportional to the displacement rate (figure

5b). By calculating the slope of the "slope vs. displacement" line, I can calculate a displacement rate from the slope of a graph of my actual data (figure 4).

In a similar manner, I was able to estimate the time when the bottom of the scarp was exposed, which is when I assume surficial displacement ended. I did this by using the model to determine the relationship between [^{36}Cl] of the sample taken from the very bottom (000 position) of the scarp and the displacement rate. I already calculated the displacement rate of the fault, so I can determine what [^{36}Cl] should be. The difference between the actual [^{36}Cl] and the model [^{36}Cl] from the scarp base is the result of surficial exposure after faulting ended. The age when faulting ended can then be easily calculated by dividing that difference by the tilted surface production rate (figure 5c).

A major problem with using this model is that it does not account for the other production pathways, which when included will slightly decrease the exposure age. The model also does not correct for erosion of the upper block surface. I will eventually be able to estimate an erosion rate from the ^{36}Cl in the sample taken from the upper fault surface, and from that calculate the baseline ^{36}Cl concentration of each sample before faulting (Stone et al., 1998; Bierman et al., 1995; Bierman, 1994; Dockhorn, 1991; Liu et al; 1994).

At the very least, I know that the ^{36}Cl content of my rocks decrease with depth down the scarp, with a pattern that implies isotope accumulation during faulting (if the fault "broke" all at once, the [^{36}Cl] in all the lower samples should be the same). Once I finish collecting chemical data, I will be able to fully develop the interpretive numerical model. Preliminary model interpretations are exciting, in that they are the only estimates for the rate of growth of this particular fault scarp.

Description of work remaining

- finish AMS work
- finish ICP work
- do ICP-MS work
- do Cl analyses
- finish developing the model (and *using* the model to calculate displacement rates)

- continue writing (I've started writing methods sections)
- decide how to deal with the displacement history/earthquake relationship issue
- error analysis

Detailed timeline for completion of research

October: Finish ICP, start and finish (?) Cl analysis, continue working on model (start learning MATLAB), continue writing rough methods sections as I develop them
November: Go to Livermore and run AgCl samples, start ICP-MS , reprocess any ambiguous or failed AMS samples, work on model, continue writing methods sections
December: Finish any remaining chemical analyses, work on model
January: Work on model, begin writing results and interpretations
February: Continue writing, work on model
March: Continue writing, work on figures
April: Turn in first draft to committee members
May: Revise thesis, NSF summer salary support
June: Revise thesis, NSF summer salary support
July: Revise thesis, NSF summer salary support
August: Turn in defendable draft to committee members
September: Defend thesis, turn in final draft
October: Graduate

Nahef East fault zone contour map, west end

contour interval = 5 meters

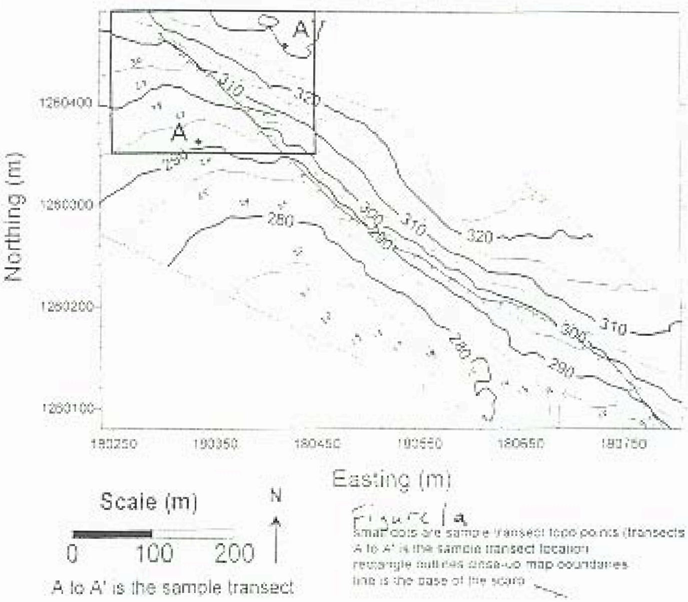


Figure 1a
small dots are sample transect topo points (transects 9 t...
A to A' is the sample transect location
rectangle outlines close-up map boundaries
line is the base of the scarp

Sample Location Transect

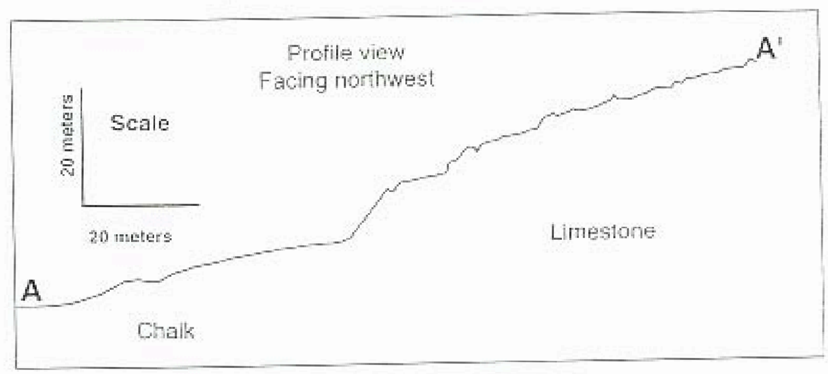


Figure 2. Profile view of sample location, A-A' corresponds to Figure 1. Here, vertical displacement is about 9 meters.

Close up of sample transect

contour interval = 5 meters

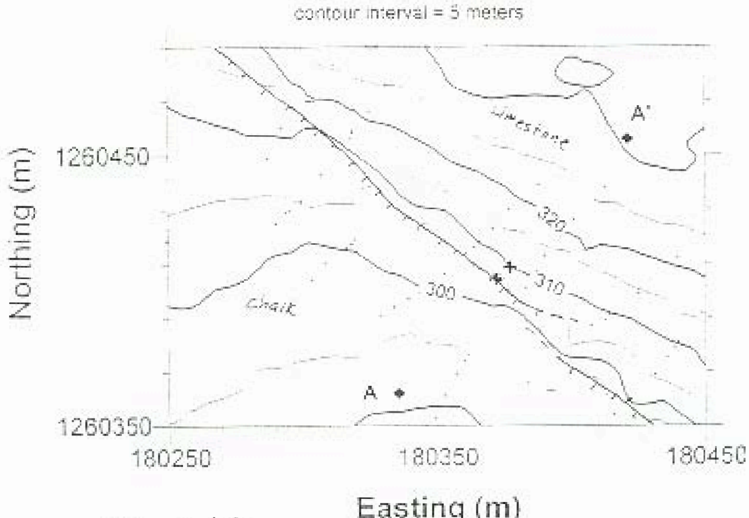


Figure 1b
small dots are sample transect topo points (transects 9 to 30)
A to A' are the sample transect endpoints
crosses mark the top and bottom of the scarp where samples were taken
line is the base of the scarp

Scarp displacement vs. lateral position

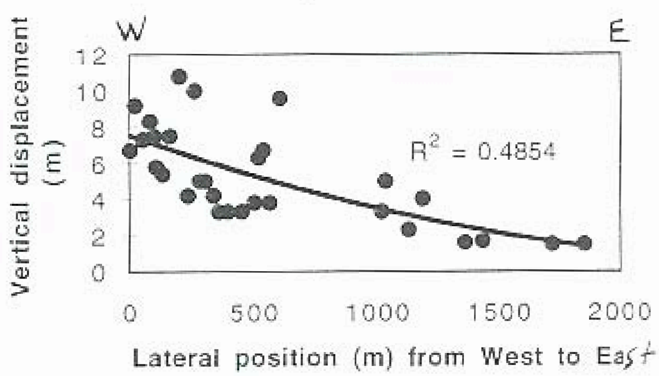


Figure 3. Vertical displacement vs lateral position on the Nahef East fault scarp. Typical normal faults have the greatest displacement in the center of the scarp. I have probably only surveyed the eastern end of this particular scarp.

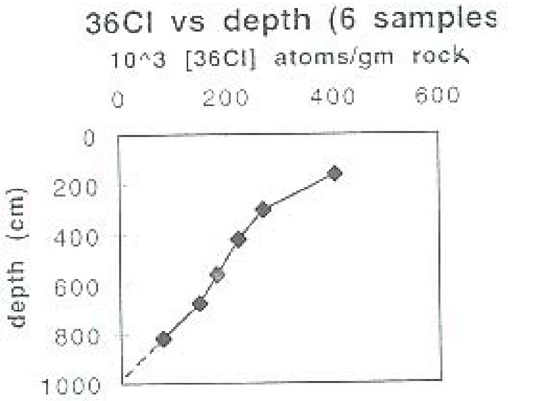


Figure 4. ^{36}Cl data from first 18 AMS samples, assuming 40 ppm Cl in each rock sample. The slope of the lower part of the scarp is proportional to the displacement rate. The upper portion deviates from the line because those samples are shallow enough to receive dosing from above.

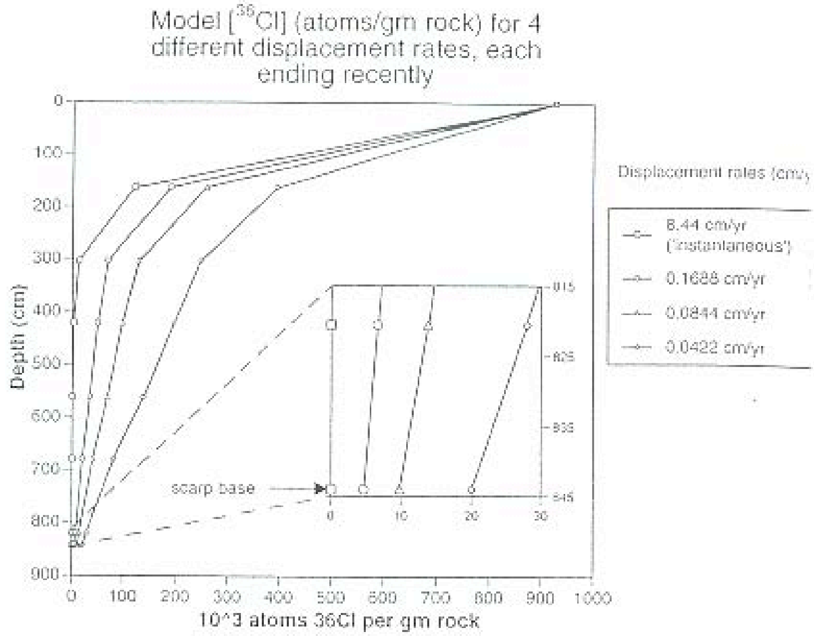
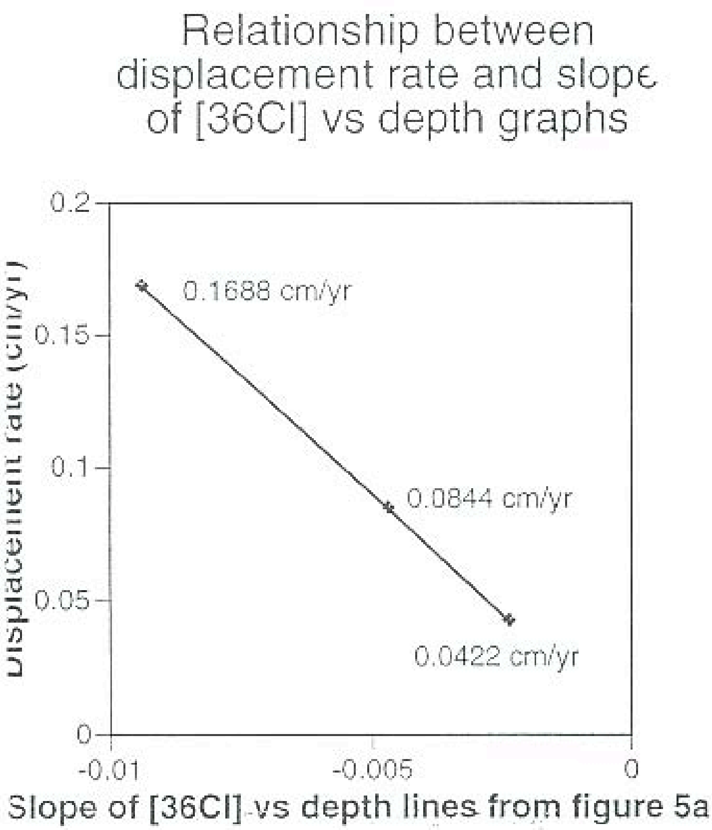


Figure 5a. [^{36}Cl] from Stella model, fault motion ending recently. There are 4 different displacement rates modeled, from the whole scarp developing at once (steep slope) to one developing over a period of 20,000 years (gentle slope). Again, upper samples are also getting dosed from above, increasing their amount of ^{36}Cl.



displacement rate = -1,796 * (slope) -0.0001428
R^2 = 9.99

Figure 5b. Relationship between [^{36}Cl] vs depth and displacement rate. Slower displacement rates correspond to less steep [^{36}Cl] vs depth plots. Slope of actual data (from figure 4) corresponds to a displacement rate of ~~0.0049~~ ~ 0,05 cm/yr

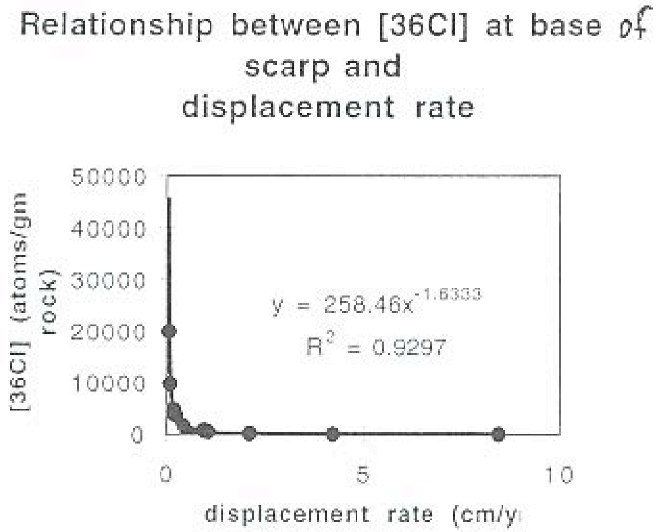


Figure 5c. Relationship between displacement rate and [^{36}Cl] produced at the base of the scarp, assuming fault motion ended yesterday. Actual [^{36}Cl] - Model [^{36}Cl] / production rate = years of exposure.

Actual = 70,000 Model = 34,500
35,500 atoms accumulate after motion ends
Prod rate ≈ 15 atoms/yr $\frac{35,500}{15}$ = 2400 yrs since motion ended

8

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