Quaternary Geochronology 19 (2014) 181–193

Contents lists available at ScienceDirect

Quaternary Geochronology

journal homepage: www.elsevier.com/locate/quageo

Research paper

Calculation of shielding factors for production of cosmogenic nuclides in fault scarps

Dmitry Tikhomirov [a,*], Naki Akçar [a], Susan Ivy-Ochs [b,c], Vasily Alfimov [b], Christian Schlüchter [a]

[a] *Institut für Geologie, Universität Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland*
[b] *Labor für Ionenstrahlphysik, ETH Zürich, Schafmattstrasse 20, 8093 Zurich, Switzerland*
[c] *Geographisches Institut, Universität Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland*

ARTICLE INFO

Article history:
Received 23 April 2012
Received in revised form
11 July 2013
Accepted 31 August 2013
Available online 17 September 2013

Keywords:
Shielding factor
Cosmogenic nuclides
Normal fault scarp
Paleoearthquake dating

ABSTRACT

The distribution of concentration of cosmogenic nuclides in fault scarps is used to determine slip histories. The complicated part is the calculation of cosmic radiation shielding by the escarpment body and the overlying wedge of the colluvial sediment. To improve reconstruction of earthquake ages and slip histories, we developed a mathematical model and corresponding MATLAB® code for computation of shielding factor profiles in fault scarp geometry. In the model, cosmic radiation received by a point of footwall is represented as unit rays attenuated exponentially in scarp geometry. This approach allows producing very precise results both for the fault scarp and the sloped surface. The code is presented as a m-function and as a stand-alone program with a user-friendly interface. Shielding factors are calculated by the code for fast neutrons or for muons and include all general shieldings: topographical, sloped surface, fault scarp surface, colluvium cover, snow cover and self-shielding. A variety of input parameters enables one to adjust the model and the code to almost all possible shielding cases. The code and stand-alone version are provided as supplementary materials and equipped with help and explanatory notes.

1. Introduction

Interpretation of isotope concentrations is a final step in surface exposure dating. It relies on calibrated production rates, on a system of scaling factors and on calculated shielding factors. The production rate gives the amount of an isotope produced per year in a gram of parent element at sea level and high latitude (SLHL). Scaling factors are used to convert the SLHL production rate to the latitude and altitude of the sampling site. Shielding factors describe the decrease of isotope production, due to attenuation of cosmic rays by local obstacles. Shielding factors cannot be tabulated, as each point of a landscape and each surface exposure sample has their own unique shielding factor. However, shielding factors can be calculated according to the local topography and the physical properties of the sample. Usually the calculation is carried out for each type of shielding, for example: topographical, which is caused by peaks and ridges surrounding a sample site; sloped surface shielding, which caused by the dip of the sampled surface; self-shielding, which is caused by the thickness of the sample; snow cover, which is important in regions with a long winter season; etc. The final shielding factor is derived as a product of all present shielding factors. Such an approach describes classic shielding cases well, but new research fields of surface exposure dating encounter more complicated cases. One such new field is the dating of bedrock fault scarp surfaces.

Dating of fault scarps with cosmogenic nuclides developed from an idea into a working methodology over the last 20 years (Zreda and Noller, 1998; Harrington et al., 2000; Mitchell et al., 2001; Benedetti et al., 2002; Hippolyte et al., 2006; Schlagenhauf et al., 2011; Akçar et al., 2012). In this method, a nuclide concentration accumulated in an exposed fault surface is translated into ages of seismically active periods and scarp displacements during these periods. To date, this method allows reconstruction of earthquakes histories for a couple of tens of thousands years in the past with an uncertainty of 500–1000 years and of about 25 cm for displacement (Schlagenhauf et al., 2010). Modern earthquake chronologies are based on instrumental data and historical observations during the last 2500 years (Ambraseys and Jackson, 1998), therefore methods operative beyond this limit are essential for producing

---

* Corresponding author. Tel.: +41 316315279; fax: +41 316314843.
E-mail addresses: tikhomirov@geo.unibe.ch, tikhomirovdmitry@gmail.com (D. Tikhomirov).

1871-1014/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.quageo.2013.08.004

long-term earthquake models. The potential of this method and the need for a better understanding of long term earthquake histories has led to both methodological and computational improvements.

The fault scarp dating method shares the same general principles with surface exposure dating. The exposed part of the normal fault scarp receives a higher cosmic ray flux than the buried part, which results in a hump-like concentration profile; exponential under colluvium and flat above (Fig. 1). The shape of the concentration profile is absolutely defined by fault scarp geometrical shielding, while the accumulated concentration value is defined by all factors used in surface exposure dating: exposure time, atmospheric attenuation, geomagnetic shielding, topographic shielding etc. In fact, this hump-like concentration profile contains both data: relative positions of the foot and the hanging walls and the exposure time through a period without seismic activity. Large earthquakes ($M > 6$) are able to displace a normal fault scarp, as is evident through footwall uplifting (Pavlides and Caputo, 2004). This vertical displacement changes geometrical shielding and a new hump-like concentration profile is superimposed on the old one with a shift equal to the displacement. Intermittently occurring earthquakes, which are rupturing the fault scarp, are represented in superposition of single hump-like concentration profiles on the footwall surface (Fig. 2). Earthquake ages and footwall uplifts can be recovered by analysis of the superposed concentration profile. Due to the complexity of this analysis, special models and calculation codes were developed over the past years (Mitchell et al., 2001; Schlagenhauf et al., 2010). In theory, the model should consist of three main parts: 1) the total production rate part, which calculates local production rates of the isotope for different incident particles and parent elements; 2) the geometrical shielding part, which calculates shielding factors specified by fault scarp geometry, sample thickness and surrounding topography; and 3) the modeling and fitting part, which assembles single concentration profiles and compares superposed profile with measured one. The third part of the model can be improved by automatic fitting, when the program varies earthquake dates and slip lengths to achieve best fit.

Analysis of a concentration profile requires continuous sampling along the scarp surface, and each sample in a profile should have enough material for isotope measurement. Limestone fault scarps fit these conditions well, therewith they are easy to sample. Starting with pioneering work by Zreda and Noller (1998), most research has been carried out on limestone scarps (Mitchell et al., 2001; Benedetti et al., 2003; Palumbo et al., 2004; Schlagenhauf et al., 2011; Akçar et al., 2012). ^{36}Cl was applied in these studies, as the only isotope for exposure dating of carbonates. Last big step in method development with ^{36}Cl was made by Schlagenhauf et al. (2010); the publication elucidated method in many details and provided reader with improved computation code.

As well as cosmogenic ^{36}Cl, cosmogenic ^{14}C (Harrington et al., 2000) and ^{10}Be (Hippolyte et al., 2006; Kong et al., 2010) have also been applied to fault scarp dating. In contrast to continuous sampling in ^{36}Cl applications, fault surfaces in these studies were sampled discontinuously, i.e. three samples from a 7 m long fault surface (Hippolyte et al., 2006), seven samples were collected from a 51 m long fault scarp (Kong et al., 2010), and two or three samples per scarp (Harrington et al., 2000). Discontinuous sampling does not allow analyzing the concentration profile along the fault scarp. However, such approach is similar to classical surface exposure dating and allows determining average age of scarp formation and/or average slip rate.

Normal fault scarps have a complicated geometry, which goes beyond the scope of the classic way of shielding factor calculation. However, proper calculation of geometrical shielding factors is the important constituent of analysis for fault scarp dating. In this paper we develop a realistic mathematical model and respective MATLAB® code for shielding factors calculation in fault scarp geometry. In the model, cosmic radiation received by a given point on a fault scarp is represented as unit rays exponentially attenuated in the scarp geometry. This approach allows calculation of complicated shielding cases and gives comprehensive solutions for fast neutrons as well as good approximations for muons. Besides fault scarp shielding, the model includes all common shielding cases: topographical, sloped surface, self-shielding and snow cover. The respective code is presented as stand-alone program with user friendly interface and as MATLAB® m-function to supplement other codes for paleoearthquake reconstruction based on cosmogenic nuclide data.

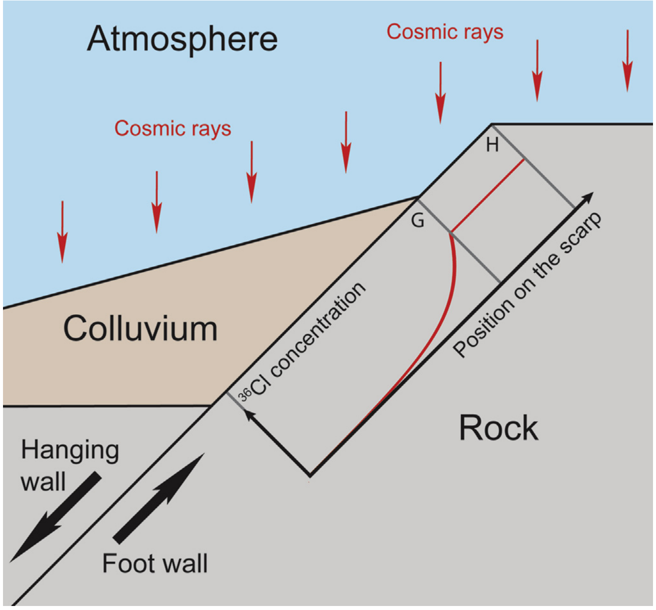

Fig. 1. Simplified concentration distribution accumulated by the footwall surface during steady period of exposure without fault scarp displacement (Akçar et al., 2012).

In the following chapter the theoretical basis of the calculation of fault scarp shielding factors are elucidated. The second chapter gives overview of the code and serves as a manual for the stand-alone version. The discussion chapter provides a comparison to other shielding calculators, an outlook on the implementation of the code into a final fault scarp dating tool and analysis of parameter variation.

2. Model

2.1. Classic shielding cases

Secondary cosmic ray particles, which cause atomic transmutation, impinge upon terrestrial objects from each point of the celestial hemisphere. The flux of secondary cosmic rays depends on the inclination angle of the observed hemisphere point and has its maximum at the zenith point. A spherical coordinate system is the most suitable way to describe the flux distribution. In a geological application, the inclination of the point is measured from the horizontal plane and the azimuth is measured in a clockwise direction from north. According to this system of coordinates, the angular distribution of cosmic ray flux can be well represented as follows:

$$F(\theta) = F_0 \sin^m(\theta) \tag{1}$$

where F_0 is the cosmic ray flux at zenith point, particle cm^{-2} s^{-1}; θ is the inclination angle, degrees; m is the cosmic rays angular