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Autor: Tschudi, Silvio / Schäfer, Jörg M. / Borns, Harold W.

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Surface exposure dating of Sirius Formation at Allan Hills nunatak, Antarctica: New evidence for long-term ice-sheet stability

SILVIO TSCHUDI[1], JÖRG M. SCHÄFER[2], HAROLD W. BORNS[3], SUSAN IVY-OCHS[4], PETER W. KUBIK[5] & CHRISTIAN SCHLÜCHTER[6]

Key words: East Antarctic Ice Sheet, Sirius Formation, Allan Hills, cosmogenic nuclides

ABSTRACT

The Allan Hills nunatak (AHN) hosts the northernmost known outcrop of the glacigenic Sirius Formation (SF) along the Transantarctic Mountains, a glacigenic deposit that is key in the understanding of the past behavior of the East Antarctic Ice Sheet (EAIS). So far, this understanding was based on chronological information about SF restricted to the inner Dry Valleys. In the present study, SF has been dated outside the Dry Valleys, providing (1) new regional chronological information and (2) new arguments for a long-term landscape and ice-sheet stability. Surface exposure dating (SED) with cosmogenic ^{10}Be, ^{26}Al and ^{21}Ne, applied on boulders of the SF and on outcropping bedrock directly underlying the SF, suggests a single and continuous period of exposure without significant coverage (e.g. by ice) of at least 2 Ma. The presented data are minimum exposure age for the SF, suggesting a deposition during the Late Pliocene or earlier. They also imply that EAIS has never overflown AHN again after that time, indicating long-term stability of the EAIS in the area around AHN since at least Late Pliocene time. Our study therefore supports the view that cold and hyperarid climate persisted over many millions of years also in areas outside the Dry Valleys.

ZUSAMMENFASSUNG

Der Allan Hills Nunatak (AHN) birgt den nördlichsten bekannten Aufschluss der glazigenen Sirius Formation (SF) entlang des Transantarktischen Gebirges. Diese glaziale Ablagerung ist essenziell für das Verständnis vergangener Fluktuationen des Ostantarktischen Eisschildes (EAIS). Bislang basierte dieses Verständnis auf chronologischen Arbeiten an der SF im Gebiet der inneren Dry Valleys. Im vorliegenden Artikel wurde die SF ausserhalb der Dry Valleys datiert, um (1) neue regionale chronologische Informationen und um (2) neue Argumente für eine weitreichende Landschafts- und Eisstabilität zu gewinnen. Oberflächenaltersbestimmung (SED) mit kosmogenem ^{10}Be, ^{26}Al und ^{21}Ne, angewendet an Oberflächen von Blöcken der SF und an anstehendem Grundgestein, das im Liegenden der SF aufschliesst, deutet auf eine einzelne und kontinuierliche Bestrahlungsperiode ohne signifikante Bedeckung (z.B. durch Eis) von mindestens 2 Ma hin. Die präsentierten Daten sind minimale Expositionsalter für die SF, hinweisend auf eine spätpliozäne oder frühere Ablagerung. Sie implizieren auch, dass das EAIS den AHN seit dieser Zeit nicht mehr überflossen hat. Dies deutet auf eine langanhaltende Stabilität des EAIS im Gebiet des AHN seit mindestens Spätpliozäner Zeit hin. Unsere Studie unterstützt deshalb die Sicht, dass kaltes und hyperarides Klima über einen Zeitraum von Millionen von Jahren auch ausserhalb der Dry Valleys angedauert hat.

Introduction

The Allan Hills nunatak (AHN), Central Victoria Land Antarctica (76°42' S, 159°40' E), more than 150 km outside the Dry Valleys, is a very sensitive test area for a waxing East Antarctic Ice Sheet (EAIS). Gentle slopes, rising from the northern Manhaul Bay of the nunatak towards the south (Fig. 1), easily enable the overflow of the nunatak by ice (Drewry 1982; Nishio & Annexstad 1979). On the nunatak, different generations of glacial deposits are observed. Among them, the northernmost outcrop of Sirius Formation (SF) is identified (see Borns unpublished, referenced in Denton et al. 1991), a key deposit in the discussion about ice sheet dynamics of the EAIS. Its age determination however is crucial and controversial (see e.g. Miller & Mabin 1998 and references therein). Harwood & Webb (1998) and Webb et al. (1984) use diatoms from SF sediments to determine a Pliocene deposition age. This is questioned by e.g. Denton et al. (1993), who believe

[1] Institute of Geology, University of Berne, 3012 Berne, Switzerland; current address: Swiss Reinsurance Company, 8022 Zürich, Switzerland
[2] Institute of Isotope Geology and Mineral Resources, ETH Zürich, 8092 Zürich, Switzerland; current address: Lamont-Doherty Earth Observatory, Palisades, NY 10964, USA
[3] Institute for Quaternary and Climate Studies, University of Maine, Orono, ME 04469-5790, USA
[4] Institute of Particle Physics, ETH Hönggerberg, 8093 Zürich, Switzerland
[5] Paul Scherrer Institut c/o Institute of Particle Physics, ETH Hönggerberg, 8093 Zürich, Switzerland
[6] Institute of Geology, University of Berne, 3012 Berne, Switzerland

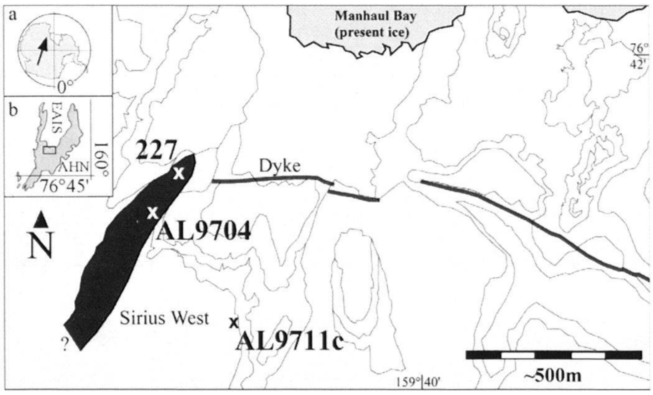


Fig. 1. Schematic overview of the sampling area at the Allan Hills nunatak with sample locations. The thin gray lines correspond to bedrock cliffs of varying heights (2 m up to 10 m). Note that the scale is only qualitatively estimated.

that the diatoms are windblown and therefore not in situ. Surface exposure dating (SED) with cosmogenic nuclides sheds light on the age of SF sediments and recent studies in the inner Dry Valleys present exposure ages up to 10 Ma (Schäfer et al. 1999), which clearly indicates a Pre-Pliocene deposition of the SF. This in turn supports a long-term stability of the EAIS during the past millions of years. However, age determination and therefore arguments for a long-term stability of the EAIS are restricted to the inner Dry Valleys (Brook et al. 1995, Bruno et al. 1997, Ivy-Ochs et al. 1995; Ivy-Ochs et al. 1997; Schäfer et al. 1999) and long-distance extensions of conclusions drawn from studies within the inner Dry Valleys to a wider area along the Transantarctic Mountains are questioned (see e.g. Van der Wateren et al. 1999).

More chronological data of SF deposits outside the Dry Valleys are therefore needed for a further understanding of the past behavior of the EAIS within a wider geographical frame. The goal of this study was thus to extend the chronological database to the north of the Dry Valleys into the AHN with SED. To recognize methodological problems like prior exposure and significant muonic contribution (both would lead to overestimated minimum exposure ages), a multi-nuclide approach with radioactive and stable cosmogenic ^{10}Be, ^{26}Al and ^{21}Ne was performed. This approach allows the determination of (1) long-term shielding of the samples from cosmic radiation (where radioactive decay would deplete the concentration of the nuclide with the shorter half-life) and (2) long-term muonic contribution (where only ^{10}Be and ^{26}Al, but no ^{21}Ne is produced, resulting in non-consistent exposure ages).

Geological setting and methods

At the AHN, the SF is found on the northern slope towards Manhaul Bay and on a plateau to the west ("Sirius West" in Fig. 1). It mainly consists of thin grayish and semi-lithified tillite overlain by numerous boulders with a wide variety in size and lithology (i.e. local dolerite and Beacon sandstone, but also foreign granite). Weathering is prominent and boulders disintegrate in situ. Most of the boulders are just overlying the drift, but some are partly embedded. This leads us to assume that the original drift was thicker than it is today, and that we probably observe an erosional relict of basal till. For direct dating of the SF at AHN, we have chosen two boulders of the western SF ("Sirius West" on Fig. 1): Sample 227, a rather small (< 1 m^3), well-rounded and hard quartzite lying on the SF, and sample AL9704, a coarse-grained sandstone boulder that is directly embedded into the SF drift to a depth of about 10 cm, indicating an in situ position in the SF (Tab. 1). The total size of boulder AL9704 is ~ 1 m^3 and the sampled surface perches 30 cm above ground level at the top of the boulder. In contrast to sample 227, weathering and erosion are obvious.

The content of cosmogenic nuclides in outcropping bedrock reflects a long-term equilibrium between production and decay or erosional processes. Discrete erosive events, like abrasion through an advancing glacier (Cuffey et al. 2000; Atkins et al. 2002), would strikingly influence this system by zeroing out the cosmological signal (i.e. resetting the "cosmological clock" to zero). SED analysis on bedrock in glacially reworked areas therefore yields the time period since re-exposure to cosmic radiation, i.e. the time period since deglaciation (Karhu et al. 2001). Consequently, a bedrock sample taken close to a basal glacial formation should yield an exposure age comparable to the age of the formation itself. At the AHN, Sample AL9711c was taken from horizontally outcropping coarse-grained Beacon sandstone, about 450 m away and 30 m lower in altitude than SF (Fig. 1). It is highly likely that this site was also covered by the glacial advance causing the Sirius de-

Table 1. Details of Allan Hills nunatak samples.

Sample	Lithology	Altitude (m)	Thickness (cm)	Weight (g quartz)	^{9}Be spike (10^{-3} g)	Comment
227	Quartzite	1,730	1.25	9.109	0.5	Clast
AL9704	Coarse sandstone	1,745	1.5	7.041	0.3	Embedded clast
AL9711c	Coarse sandstone	1,705	0.8	7.895	0.3	Bedrock

Sample	$^{9}Be/^{10}Be$ (10^{-12})	$^{27}Al/^{26}Al$ (10^{-12})	^{20}Ne (10^{9} at g^{-1})	$^{21}Ne/^{20}Ne$ (10^{-3})	$^{22}Ne/^{20}Ne$ (10^{-1})	^{10}Be (10^{7} at g^{-1})	^{26}Al (10^{7} at g^{-1})	$^{21}Ne_{cosm}$ (10^{7} at g^{-1})
227	4.394 ± 0.202	16.217 ± 0.762	32.05 ± 0.12	5.954 ± 0.110	1.050 ± 0.006	1.61 ± 0.11	8.79 ± 0.61	9.60 ± 0.36
AL9704	11.582 ± 0.209	161.429 ± 1.937	7.36 ± 0.11	32.041 ± 0.657	1.297 ± 0.026	3.30 ± 0.18	15.21 ± 0.78	21.40 ± 0.59
AL9711c	10.447 ± 0.199	50.034 ± 0.550	12.66 ± 0.08	16.492 ± 0.301	1.175 ± 0.011	2.65 ± 0.14	12.72 ± 0.65	17.13 ± 0.40

Table 2. MS measured ^{10}Be, ^{26}Al and ^{21}Ne concentrations. The errors are given at 1-σ confidence level for sample and blank. Radionuclides include a 5 % uncertainty for possible chemical processing variability (Ivy-Ochs 1996). Ne data are given within 1-σ confidence level, including statistical, sensitivity and mass-discrimination errors. Errors due to uncertainties of calibration gas amounts are not included but should be < 3 %. See also Fig. 3.

Sample	^{10}Be age (10^{6} years)	^{26}Al age (10^{6} years)	^{21}Ne Age (10^{6} years)	Max. erosion rate (cm my^{-1}), calc. with ^{10}Be	^{26}Al	^{21}Ne
227	* 0.8 ±0.08	0.82 +0.11 -0.10	1.03 ±0.15	63 ± 6	48 ± 8	56 ± 8
	# 0.63 ±0.07	0.66 +0.09 -0.08	0.82 ±0.12	79 ± 7	63 ± 9	70 ± 10
AL9704	* 2.12 +0.26 -0.23	(2.91) (**) (-0.79)	2.27 ±0.31	17 ± 2	(4 ± 3)	25 ± 3
	# 1.56 +0.19 -0.17	1.74 +0.44 -0.31	1.82 ±0.24	25 ± 3	13 ± 4	32 ± 4
AL9711c	* 1.57 +0.16 -0.15	1.71 +0.38 -0.28	1.87 ±0.26	26 ± 3	14 ± 4	31 ± 4
	# 1.19 +0.13 -0.12	1.23 +0.21 -0.17	1.49 ±0.20	36 ± 4	24 ± 5	39 ± 4

* Calculation of exposure ages with production rates of Kubik et al. (1998) and Niedermann (2000), respectively. Scaling after Lal (1991). Correction of sample thickness according to Masarik & Reedy (1995).
# Calculation of exposure ages with production rates of Stone (2000) and Niedermann (2000), respectively. Scaling after Stone (2000). Correction of sample thickness according to Lal (1991).
** ^{26}Al in saturation, no age calculation possible

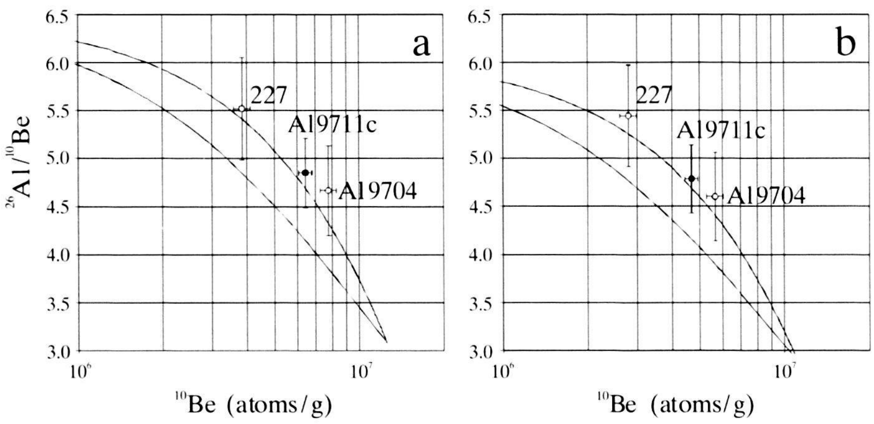
Table 3. Calculated exposure ages and maximum erosion rates for the AHN sample set. Calculations were done according to (e.g.) Nishiizumi et al. (1991). No shielding-correction from surrounding landscape had to be preformed. The age uncertainties include the uncertainties described in Table 2 and the errors of the used reference production rates (Kubik et al. 1998; Niedermann 2000; Stone 2000). Note that the ^{26}Al concentration of sample AL9704 is close to saturation, which means that the calculated age and erosion rate are methodologically very sensitive to any uncertainty and thus of limited use. Therefore, they were not considered for our implications and conclusions.

posit, as it lies lower in altitude than the AL9704 site. The lithology of AL9711c shows reddish oxidation features and it directly extends underneath the "Sirius West" formation. Both sandstone samples AL9704 and AL9711c are of similar lithology (i.e. Beacon sandstone) with comparable erosive behavior, so that age differences should not reflect different erosion rates.

Quartz was separated according to Kohl & Nishiizumi (1992) and the chemical separation of ^{10}Be and ^{26}Al was done following Nishiizumi et al. (1989), Kohl & Nishiizumi (1992) and Ivy-Ochs (1996). The concentrations of the cosmogenic nuclides ^{10}Be and ^{26}Al were measured by accelerator mass spectrometry (AMS) at the Zurich tandem accelerator facility of the Paul Scherrer Institut (PSI) and the ETH (Synal et al. 1997). For the neon analysis, we handpicked a split of the chemically separated quartz used for the radionuclide analysis (extensive etching in 5 % HF over several days). Herewith, we removed quartz grains containing ingrowths of e.g. zircon, muscovite or biotite, to minimize the contribution of nucleogenic neon. The neon analysis followed the protocol given in Bruno et al. (1997). The Ne was analyzed in a non-commercial all-metal magnetic sector mass-spectrometer ("Tom Dooley", 90°, 210 mm radius) equipped with a Baur-Signer ion source, whose sensitivity is essentially constant in the pressure range relevant for this work. Sensitivity variations and mass-fractionation effects of the mass spectrometer were quantified by analysis of a pure-neon standard (mixed at the ETH Zurich gas mixing facility) after each sample (approximately five per day). Measurements were performed at the Institute of Isotope Geology and Mineral Resources (IGMR) of the ETH Zurich.

Results

The results are summarized in Tables 2 and 3, where measured nuclide ratios and concentrations, as well as minimum exposure ages and maximum erosion rates are presented. Furthermore, all data are plotted in Be-Al two-nuclide plot (Figs. 2a and b) to evaluate possible pre-exposure (see e.g. Gosse & Phillips 2001). Independently, Fig. 3 indicates a two-compo-



Figs. 2a and b. Two-nuclide plots ($^{26}Al/^{10}Be$ versus ^{10}Be) of all samples shown for both sets of reference production rate and atmospheric scaling mentioned in the text (Fig. 2a calculated with Kubik et al. 1998 and Lal 1991, Fig 2b calculated with Stone 2000). All concentrations are normalized to sea level and high latitude. Error bars include 1-σ error of the AMS measurement and a 5 % uncertainty for possible chemical processing variability (Ivy-Ochs 1996). All samples fall within errors on the zero-erosion line, which indicates zero or only minor erosion during exposure without significant coverage (e.g. by ice).

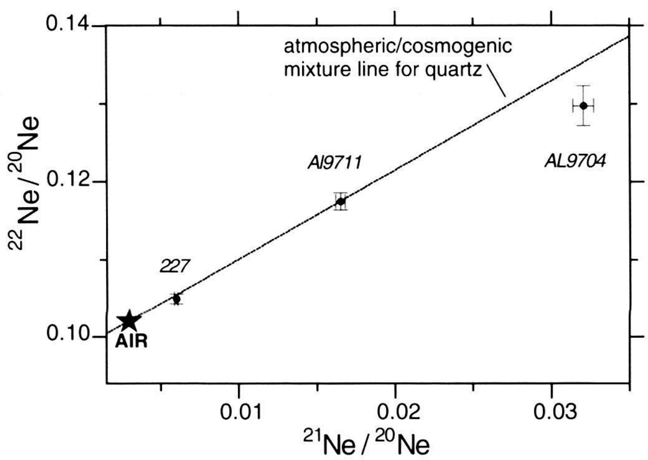


Fig. 3. Neon three-isotope plot for all three samples given within 1-σ confidence level. Sample to 227 and Al9711 plot directly on the two-component mixture line of atmospheric and cosmogenic neon from quartz (Schäfer et al. 1999), sample Al9704 plots very close to it, indicating only minor contributions of other neon components. This holds true for both rock-types investigated here, sandstone and quartzite. Therefore, we calculate the Ne-exposure ages from the ^{21}Ne excess above the atmospheric value (the ^{20}Ne-concentration is assumed to be entirely atmospheric; the atmospheric $^{21}Ne/^{20}Ne$ = 0.002959 is assumed to be precisely known).

nent mixture of cosmogenic and atmospheric neon with no indication for nucleogenic contribution.

Recent discussion about adjusted scaling functions for special Antarctic atmospheric conditions (Stone 2000) and reevaluated muonic contribution (Heisinger et al. 1997) affect the production rates of cosmogenic nuclides and therefore the calculated exposure ages. For the geographical setting of our sample set at AHN, these effects are in the order of up to about 30 % (Fig. 3 in Stone 2000). We therefore decided to present our data using different sets of production rates and scaling functions, namely the reference production rates of Kubik et al. (1998), scaled according to Lal (1991) and the rates and scaling of Stone (2000) for the radioactive nuclides, and the rates of Niedermann (2000) scaled according to Lal (1991) and Stone (2000) for the stable nuclide, respectively. Note that even though the numerical ages and erosion rate estimations of our sample set change with the chosen reference production rate and scaling function, the following implications are not affected by this choice.

Discussion and implications

From the triple-nuclide analysis we conclude that the sampled surfaces experienced only a single period of exposure without long-term coverage (e.g. by an advanced EAIS), as (1) all data plot within errors on the zero erosion line of the two-nuclide plot (Figs. 2a and b) and (2) the calculated exposure ages of radioactive and stable nuclides are consistent with each other (Table 3). The given ages therefore represent true minimum ages of the sampled surfaces, with weighted averages of 0.84 ± 0.06 Ma (0.67 ± 0.05 Ma) for sample 227, 2.19 ± 0.20 Ma (1.67 ± 0.14 Ma) for sample AL9704 and 1.66 ± 0.13 Ma (1.27 ± 0.10 Ma) for sample AL9711c, respectively. We believe that the discrepancy between the samples 227 and AL9704 is due to their different position within SF (sample 227: loosely lying on the SF, sample AL9704: partly embedded within SF). Recent work of Atkins et al. (2002) describes the presence of post-Sirius glacial advances into AHN up to the Sirius West site (Fig. 1 in Atkins et al. 2002). Thus, sample 227 could have been deposited as loose debris on the older SF. Our chronological conclusions are therefore based on sample AL9704 only. Taking this into account, the SF bears an age of 2.19 ± 0.20 Ma (1.67 ± 0.14 Ma) at the AHN (weighted average from ^{10}Be and ^{21}Ne). The bedrock sample AL9711c yields a similar, but younger exposure age of 1.66 ± 0.13 Ma (1.27 ± 0.10 Ma). Note that the bedrock sample AL9711c origins from a lower altitude than the AL9704 site, causing a relatively longer coverage by the retreating ice. We thus believe that the age of the bedrock sample strongly supports the Late Pliocene age of SF, as it points to a site-deglaciation at some 1.7 Ma ago. For the maximum erosion rates, the calculations yield very low values, all below 1 m my^{-1}, indicating very slow landscape forming processes (Table 3). These values are comparable to earlier estimates that were also determined with SED on AHN bedrock samples (Nishiizumi et al. 1991).

The SF deposits at AHN were deposited at least 2.2 Ma (1.7 Ma) ago, implying a Late Pliocene or older age. Since then, the EAIS has never overflown the AHN above our sample site (i.e. above 1,700 m). This is supported by the bedrock sample, which indicates ice-free conditions since at least 1.7 Ma (1.3 Ma). Our findings are in accord with earlier SED analyses on bedrock samples taken closer to the present ice front, indicating ice-free conditions for AHN for at least 500 ka for lower altitudes (Nishiizumi et al. 1991). Our data indicate that the EAIS did not advance extensively into the AHN since Late Pliocene time, indicating absence of significant EAIS growing into AHN and requiring stability of the EAIS for millions of years. This finding is consistent with conclusions derived from studies on SF within the inner Dry Valleys (Brook et al. 1995; Bruno et al. 1997; Ivy-Ochs 1996; Ivy-Ochs et al. 1997; Schäfer et al. 1999). It therefore contradicts the conclusions of Van der Wateren et al. (1999), who state differential glacial histories of the Dry Valleys region compared to Central or Northern Victoria Land.

Conclusions

Our triple-nuclide study on surfaces of boulders and bedrock at the AHN shows that the presented exposure age of 2.2 Ma is a true minimum age for the last significant advance of the EAIS into the AHN, reaching altitudes above 1,700 m. This site, being a unique archive reflecting the past fluctuations of the EAIS due to gentle slopes towards the inflowing ice, is lying outside the well-investigated inner Dry Valleys region, where many studies indicate stable and constantly dry and hyperarid climate over many millions of years. The present study gives evidence for similar conditions outside the Dry Valleys by absence of significant glacial advances of the EAIS over millions of years. We therefore believe that the conclusions drawn from the Dry Valleys block can be extended along the Transantarctic Mountains to at least the area of AHN.

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