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Exposure dating (^{10}Be , ^{26}Al) of natural terrain landslides in Hong Kong, China

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ABSTRACT

We successfully apply exposure dating using cosmogenic nuclides to natural terrain landslides in Hong Kong. Forty-five samples from eight landslide sites were exposure dated using ^{10}Be , and a subset of six samples was also dated using ^{26}Al . The sites comprised four large, deep-seated landslides featuring well-preserved rock scarps and associated debris lobes; two sites of rock and boulder fall; and two sites where scarps only are preserved. All of the deep-seated landslides gave ages within the last 50,000 yr, and the largest landslide gave an age of ~32,000 yr. The youngest (~2000 yr) and oldest (~57,000 yr) landslide events dated came from the two sites of rock and boulder fall. Exposure ages from the deep-seated landslide scarps generally gave the most internally consistent ages for the landslides. However, only in rare cases did the landslide scarp ages overlap with those of boulders in the associated debris. Generally, boulders in the debris appeared to contain significant inheritance of cosmogenic nuclides from previous exposure and so yielded ages greater than those from the scarps. Surface exposure ages of ~285,000 yr from boulders in the debris of

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two deep-seated landslides provide minimum ages considered to represent the original rock surfaces. This study has shown that it is possible to measure exposure ages of surfaces associated with large landslides from 70,000 yr down to a few thousand years old, despite low cosmogenic isotope production rates in Hong Kong due to low latitude and low altitude.

Keywords: Al-26, Be-10, cosmogenic elements, exposure age, Hong Kong, landslides.

INTRODUCTION

In situ-produced cosmogenic nuclides (^{10}Be , ^{26}Al) are now widely used for dating geomorphological events that have occurred within the last few million years. The most common application is for exposure dating of glacial surfaces (e.g., Bierman *et al.*, 1999; Barrows *et al.*, 2001, 2002). Cosmogenic nuclides have also been used to date (1) fault movements (e.g., Zreda and Noller, 1998), (2) volcanic landforms (e.g., Licciardi *et al.*, 1999), (3) meteorite impacts (e.g., Phillips *et al.*, 1991), and (4) periglacial deposits (e.g., Barrows *et al.*, 2004).

Dating ancient landslides has historically presented a significant challenge for traditional dating methods. The relatively short life-span of trees and shrubs, usually limited to a few decades, means that estimates of landslide ages based on the assessment of vegetation cover and revegetation rates may only be reliable for very young (<300 yr) landslides. Dating buried organic material using radiocarbon is possible in only some circumstances. Exposure dating, however, has the distinct advantage over other dating methods of directly dating rock surfaces, so no assumptions need be made, as are required with radiocarbon dating as to whether the organic material was contemporaneous with the landslide event. Prior to this study, there have been relatively few attempts to exposure date ancient landslides (e.g., Bierman *et al.*, 1995; Nichols *et al.*, 2000). Ballantyne *et al.* (1998) used exposure dating to investigate the timing of postglacial landslides in Scotland. In Austria, cosmogenic nuclide data from a landslide were used in an attempt to calibrate the ^{10}Be production rate at Kfels landslide (Kubik *et al.*, 1998). Successful dating of the landslide using radiocarbon allowed a production rate to be calculated that is quite similar to that derived elsewhere (Stone, 2000).

Approximately 50% of Hong Kong's land area (1103 km², the area of the Hong Kong Special Administrative Region, China) comprises steep **natural terrain**¹ sloping at angles greater than 30°. With most of the population being concentrated in the flat-lying urban areas (215 km²), and with the shortage of land available for housing and economic activities, new developments increasingly encroach on the surrounding natural terrain, leading to intense pressures on the environment. Approximately 300 natural terrain landslides occur in Hong Kong each

year (King, 1999), and between the years 1982 and 1999, ~800 natural terrain landslides were reported (King, 1999) as affecting urban developments. Thus, landsliding is an important mechanism controlling landscape evolution in Hong Kong and has significant economic implications. Despite the difficulty in dating ancient landslides, larger relict features in Hong Kong have generally been considered to be several 10s to 100s, rather than 1000s, of years old (Evans, 1998; Murray, 2001; Ng *et al.*, 2003). These notional ages have fallen within the approximate design life of engineering structures in Hong Kong, and therefore have influenced the development of landslide hazard risk management strategies (Ng *et al.*, 2003). However, more accurate estimates of landslide age are now required if improved assessment and reliable and cost-effective mitigation of natural terrain hazards is to be achieved.

One of the Hong Kong SAR Government's policy objectives is to advance the understanding of the causes and mechanisms of natural terrain hazards, so as to improve the reliability of landslide preventive or remedial works. Assessment and mitigation of natural terrain hazards depend on the interpretation of historical landslide data and consideration of the possible return periods of natural terrain failures. The estimation of return periods, based on historical landslide data, assumes some constancy in the environmental controls of the landslides. Given the extreme changes in sea level and known climatic fluctuations that have occurred during the last 10–15,000 yr (Thomas, 1994; Fyfe *et al.*, 2000), this assumption requires confirmation. Therefore, knowledge of relict natural terrain landslide chronologies is essential not only for providing more reliable constraints on landscape evolution and estimation of return periods, but also for understanding the causes and mechanisms of landslides.

In this paper, we apply exposure dating to large, deep-seated landslides, and substantial rockfall events in Hong Kong. This is part of a larger dating study of natural terrain landslides in Hong Kong (Sewell and Campbell, 2005), which includes the establishment of relative chronologies based on aerial photograph interpretation, and dating of landslide deposits using optically stimulated luminescence (OSL) and radiocarbon (^{14}C -AMS). We demonstrate that exposure dating using ^{10}Be and ^{26}Al can be applied successfully to landslides in Hong Kong. Furthermore, the sensitivity of the analytical techniques is sufficiently high to measure exposure ages of surfaces only a few thousand years old, despite the seemingly unfavorable circumstances in Hong Kong of low latitude and low altitude.

¹Natural terrain follows the definition given in Ng *et al.* (2003), namely, "terrain that has not been modified substantially by human activity but includes areas where grazing, hill fires, and deforestation may have occurred."

SAMPLING STRATEGY

Exposure dating is based on the accumulation of cosmogenic nuclides in a rock surface first exposed to cosmic radiation. Most cosmogenic nuclides are created in the uppermost 3 m of rock. To date landslides, inheritance from any previous exposure must be avoided. Accordingly, the landslides must be of sufficient magnitude to generate freshly exposed surfaces. The surface to be dated also needs to have remained stable, i.e., in the same geometry, during its exposure history, and to have experienced negligible weathering.

There are two options for applying exposure dating to landslides: dating scarp faces and dating blocks within debris lobes. Potentially, exposure ages both from the scarp and from blocks within the debris could give the age of detachment of the landslide from its source area. However, several factors can bias exposure ages in these settings. For scarp faces, exposure ages can overestimate the age of the landslide if a shallow (<3 m deep) surface is sampled. Similarly, exposure ages for blocks sourced from the original land surface will also appear too old. Sampling scarp faces, where there is reliable evidence that the material is in situ, has the advantage that the surface has been continually exposed in the same geometry. However, blocks within, or on top of, a debris lobe may have moved after deposition, or even been exhumed from beneath the original surface of the debris. In both scenarios, exposure ages could underestimate the age of deposition of the debris and hence of landsliding. Similarly, if material has weathered from the sampled rock surface, that age of deposition would again be an underestimate.

In this study, 45 samples were dated using ^{10}Be . A subset of six samples was also dated using ^{26}Al to investigate reproducibility of results and to identify the possibility of multiple exposure histories on blocks in the debris lobes. The availability of excellent low-level (3900 ft) and high-level (10,000 ft) aerial photographs of Hong Kong, taken in 1963 and 1964 when the general vegetation cover was much less dense than at the present day (due mainly to the activities of the largely rural population), greatly assisted (1) the identification of relict natural terrain landslides, (2) the establishment of relative chronologies among clusters of relict landslides, and (3) the development of sampling strategies for exposure dating of relict landslides.

Where possible, samples were collected both from scarp faces and from the associated debris lobes. We were careful to select rocks that did not show any unusual weathering, to minimize the possibility of inheritance. The selected deep-seated landslide sites generally exhibited >4 m high rock scarps. In cases where these could be associated with obvious debris lobes, the debris often contained very large (>5 m diameter) boulders, providing ideal sites for exposure dating and strong evidence that the lobes were the products of single large events. Multiple samples were collected from various elevations across the scarp surface, and from the flat upper surfaces of large boulders within the debris, to investigate the effects of inheritance.

Generally, the landslide features selected for exposure dating were located within clusters of overlapping natural terrain landslides. The results of direct dating, therefore, provided an opportunity to assess the relative chronology of the overlapping landslides previously established by aerial photograph interpretation. Accordingly, the detailed characteristics of the sample sites on the following figures include the location and extent of surrounding landslide features. Site data for the samples collected for the study are summarized in [Table 1](#).

SITES

Eight natural terrain landslide sites from across Hong Kong were selected for study ([Fig. 1](#)). These comprised four large, deep-seated landslides featuring well-preserved scarps, mainly in rock, and associated debris lobes (Sham Wat Debris Lobe, Sunset Peak West, Tsing Yi, and Ap Lei Chau); two sites of rock and boulder fall (Lion Rock and Fei Ngo Shan); and two deep-seated landslides with scarps preserved, but no debris that could be related to the scars with confidence (Lai Cho Road and Mid-Levels). The sites were selected for a variety of reasons: (1) They were the subject of recent detailed investigations of instability (e.g., Lai Cho Road), (2) they were previously investigated sites associated with larger integrated studies (e.g., Sham Wat Debris Lobe, Mid-Levels, Ap Lei Chau), and (3) they were close to existing developments (e.g., Lion Rock, Fei Ngo Shan, Tsing Yi, Sunset Peak West).

Deep-Seated Scarp and Debris Lobe Sites

Sham Wat Debris Lobe

The largest landslide feature we studied is located at Sham Wat in western Lantau Island, and is known as the “Sham Wat Debris Lobe” ([Fig. 2](#)). The debris lobe was previously the subject of a detailed investigation (King, 1998), including a preliminary dating study (King, 2001). On the basis of standard (“average large aliquot”) optically stimulated luminescence dating methods, the apparent age of the deposit was reported as ca. 35 ka. However, Murray (2001) considered this age to be a gross overestimate because using the dose distribution method, based on the assumption of incomplete bleaching, the deposit returned ages as young as 1.4 ± 0.2 ka, with a likely age range between 1 and 23 ka.

There are two main parts to the Sham Wat Debris Lobe, the main large northern debris lobe, with an estimated volume of 850,000 m³, and a subordinate southern lobe with an estimated volume of 150,000 m³. The main lobe has a well-defined source area marked by a prominent 10 m high rock escarpment, composed of porphyritic rhyolite. Numerous large boulders protrude from the surface of the debris lobe and these, together with the main scarp region, provided suitable sites for exposure dating. Ten samples ([Table 1](#)) were collected from the prominent rock escarpment forming the source area for the main lobe (SWD-01 to SWD-05), as well as large boulders (SWD-06 to SWD-10) within the associated debris ([Fig. 2](#)). Samples across the scarp

TABLE 1. SITE DATA

Sample	Latitude (°N)	Longitude (°E)	Altitude (m)	Setting	Scaling factor (nucleons)	Scaling factor (muons)	Horizon correction	Thickness (cm)	Thickness (correction)
<u>Deep-seated Scarps and Debris Lobes</u>									
Sham Wat Debris Lobe									
SWD-01	22°15'33.53	113°52'56.39	358	Scar	0.930	0.840	0.894	4.0	0.968
SWD-02	22°15'33.53	113°52'56.39	358	Scar	0.930	0.840	0.894	4.7	0.963
SWD-03	22°15'33.30	113°52'57.16	350	Scar	0.920	0.840	0.952	4.1	0.967
SWD-04	22°15'33.30	113°52'57.16	350	Scar	0.920	0.840	0.910	4.0	0.968
SWD-05	22°15'33.30	113°52'57.68	340	Scar	0.920	0.840	0.979	3.5	0.972
SWD-06	22°15'41.76	113°52'57.56	75	Boulder	0.750	0.740	0.984	2.0	0.984
SWD-07	22°15'43.29	113°52'57.84	69	Boulder	0.750	0.730	0.985	2.25	0.982
SWD-08	22°15'47.68	113°53'00.27	38	Boulder	0.730	0.720	0.986	3.5	0.972
SWD-09	22°15'44.76	113°53'01.53	45	Boulder	0.730	0.730	0.986	2.5	0.980
SWD-10	22°15'41.33	113°52'54.52	90	Boulder	0.760	0.740	0.985	1.0	0.992
Sunset Peak West									
TCR-01	22°15'13.97	113°56'43.72	480	Scar	1.020	0.890	0.852	4.0	0.968
TCR-02	22°15'14.00	113°56'43.83	486	Scar	1.020	0.900	0.852	6.0	0.954
TCR-03	22°15'14.00	113°56'43.76	482	Scar	1.020	0.900	0.950	3.5	0.972
TCR-04	22°15'13.84	113°56'43.83	490	Scar	1.030	0.900	0.851	2.8	0.977
TCR-05	22°15'17.71	113°56'25.28	215	Boulder	0.830	0.790	0.987	6.0	0.954
TCR-06	22°15'17.71	113°56'25.28	215	Boulder	0.830	0.790	0.986	2.2	0.982
TCR-07	22°15'17.20	113°56'26.15	220	Boulder	0.840	0.790	0.987	4.0	0.968
TCR-08	22°15'16.45	113°56'26.46	225	Boulder	0.840	0.790	0.985	1.75	0.986
TCR-09	22°15'16.45	113°56'26.46	225	Boulder	0.840	0.790	0.985	4.2	0.967
TCR-10	22°15'16.28	113°56'25.94	223	Boulder	0.840	0.790	0.985	2.0	0.984
Tsing Yi									
TY-01	22°20'17.95	114°06'11.59	138	Boulder	0.786	0.760	0.947	4.5	0.964
TY-02	22°20'17.37	114°06'10.68	151	Boulder	0.790	0.760	0.931	2.2	0.982
TY-03	22°20'15'.97	114°06'09.49	173	Boulder	0.810	0.770	0.922	2.0	0.984
TY-04	22°20'15'.42	114°06'08.37	190	Scar	0.820	0.780	0.905	4.75	0.963
TY-05	22°20'14.89	114°06'05.09	255	Scar	0.860	0.800	0.720	1.5	0.988
TY-07	22°20'14.83	114°06'07.81	216	Scar	0.830	0.790	0.942	5.0	0.961
Ap Lei Chau									
ALC-01	22°14'17.14	114°09'27.22	161	Scar	0.800	0.770	0.966	2.5	0.980
ALC-02	22°14'17.21	114°09'26.27	173	Scar	0.810	0.770	0.924	2.75	0.978
ALC-03	22°14'16.33	114°09'27.22	155	Scar	0.800	0.770	0.879	2.5	0.980
ALC-04	22°14'18.22	114°09'28.97	137	Boulder	0.790	0.760	0.968	5.0	0.961
<u>Rock and boulder Falls</u>									
Lion Rock									
LR-01	22°20'55.04	114°11'17.65	176	Boulder	0.810	0.770	0.973	1.5	0.988
LR-02	22°20'57.64	114°11'14.57	208	Boulder	0.830	0.790	0.947	1.5	0.988
LR-03	22°20'55.98	114°11'13.84	190	Boulder	0.820	0.780	0.964	4.5	0.964
Fei Ngo Shan									
FNS-01	22°20'15.69	114°13'02.13	162	Boulder	0.800	0.770	0.968	3.0	0.976
FNS-02	22°20'14.87	114°13'03.36	158	Boulder	0.800	0.770	0.975	2.2	0.982
FNS-03	22°20'15.30	114°13'03.53	162	Boulder	0.800	0.770	0.975	1.75	0.986
<u>Deap-Seated Scarps</u>									
Lai Cho Road									
LCR-01	22°21'05.03	114°07'45.89	109	Scar	0.770	0.750	0.847	3.5	0.972
LCR-02	22°21'05.00	114°07'45.82	110	Scar	0.770	0.750	0.703	5.7	0.956
LCR-03	22°21'05.19	114°07'46.10	111	Scar	0.770	0.750	0.854	2.0	0.984
LCR-04	22°21'05.26	114°07'46.06	109	Scar	0.770	0.750	0.789	6.5	0.950
Mid-Levels									
ML-01	22°16'38.69	114°08'35.48	420	Scar	0.970	0.870	0.815	2.5	0.980
ML-02	22°16'38.78	114°08'35.44	400	Scar	0.960	0.860	0.815	3.0	0.976
ML-03	22°16'38.65	114°08'35.37	420	Scar	0.970	0.870	0.855	3.7	0.970
ML-04	22°16'38.82	114°08'35.20	400	Scar	0.960	0.860	0.758	4.3	0.966
ML-05	22°16'38.82	114°08'35.20	400	Scar	0.960	0.860	0.758	3.0	0.976

Figure 1. Location map of landslide sites selected for the dating study in the Hong Kong Special Administrative Region.

surface came from steep (62° – 83°) well-jointed faces, more or less at similar elevations (340–358 mPD).² Large boulders sampled were generally well distributed across the surface of the debris lobe, had a minimum volume of 15 m^3 , and displayed similar weathering characteristics. Sample elevations in the debris lobe varied from 38 to 90 mPD.

Sunset Peak West

A large, deep-seated, natural terrain landslide, with a well-preserved main scarp and debris lobe, was studied on the western flanks of Sunset Peak, central Lantau Island (Fig. 3). The main

rock type is coarse to fine ash rhyolitic tuff. Ten samples (Table 1) for exposure dating were collected from the scarp and debris lobe regions of the landslide (Fig. 3). Three samples (TCR-01, TCR-02, and TCR-04) came from elevations of 480 mPD, 486 mPD, and 490 mPD, respectively, on the moderately inclined (53°) scarp surface. One sample (TCR-03, 482 mPD) came from an adjacent, inclined (40°) rock surface on the upper western flank of the scarp, although this was considered not to have contributed to the landslide, and the sample was collected mainly for control purposes. Six samples (TCR-05 to TCR-10) were collected from large (20 m^3) boulders within the debris lobe. The boulders were generally well distributed, with similar internal features (e.g., flow banding) and lithologies to the rocks in the scarp area. Sample

²Principal datum (PD) in Hong Kong is 1.23 m below mean sea level.

Figure 2. Geomorphological features, sample locations, and dating results for the Sham Wat Debris Lobe.

elevations in the debris lobe varied between 215 and 225 mPD. Samples TCR-08 and TCR-09 came from different positions on the same boulder to test for possible inheritance.

Tsing Yi

Two large landslide features were studied on the southeast side of Tsing Yi (Fig. 1). These relict features comprise two steep ($>46^\circ$) cliff areas (sheeting joint escarpment nos. 1 [SJ1] and 2 [SJ2]) composed of medium-grained granite, each characterized

by distinctive sheeting joints, and with a large accumulation of boulder-bearing debris downslope (Fig. 4).

Six samples (Table 1) were analyzed from the site. Two samples (TY-01 and TY-02) came from very large (50 m^3) boulders from the debris lobe no. 4 (DL4) debris at elevations of 138 mPD and 151 mPD, while a third boulder (TY-03) was sampled from the colluvium no. 1 (CL1) debris adjacent to the SJ1 cliff. Two samples from the cliff area (TY-04 and TY-07) came from SJ1 rock surfaces at elevations of 190 mPD and 216 mPD,

Figure 3. Geomorphological features, sample locations, and dating results for the Sunset Peak West landslide site. Legend as for Figure 2.

respectively, and one sample (TY-05) came from a rock surface on the cliff area SJ2 at an elevation of 255 mPD.

Ap Lei Chau

A large landslide (relict landslide no. 1 [RLS1]) underlain by eutaxitic fine ash vitric rhyolitic tuff, with a clearly defined main scarp and debris lobe, is located on Ap Lei Chau, to the southwest of Hong Kong Island (Fig. 5). A total of four samples (Table 1) were collected. These comprised two samples (ALC-01 and ALC-02) from the main scarp, one sample (ALC-03) from an unrelated adjacent scarp for control purposes, and one sample (ALC-04) from a boulder on the debris lobe of the main scarp. Sample ALC-01 came from a sheeting joint exposed at an eleva-

tion of 161 mPD and inclined at 30° on the edge of the main scarp. The sampled rock surface was strongly weathered, and elsewhere partly covered by a relatively thin (0.2 m) layer of surface debris, and so might be anticipated to yield an age by exposure dating that underestimated to some extent the age of formation of the surface. Sample ALC-02 came from a sheeting joint, inclined at 36° , along the crest of the main scarp, at an elevation of 173 mPD. Compared with ALC-01, the sampled rock surface was distinctly less weathered. Sample ALC-03 came from near the base of a prominent rock cliff at an elevation of 155 mPD, ~40 m southeast of the main scarp. The boulder sampled on the debris lobe of the main scarp (ALC-04) is ~4 m³ and lies at an elevation of 137 mPD.

Figure 4. Geomorphological features, sample locations, and dating results for the Tsing Yi landslide site. Legend as for Figure 2.

Rock and Boulder Fall Sites

Lion Rock

Three extremely large (1000 m^3) granite boulders (Table 1), ~300 m apart, were sampled below Lion Rock, in northern Kowloon (Fig. 1). Two of the boulders (LR-02 and LR-03) lie within, or on top of, the same colluvial unit (Fig. 6), whereas the third boulder (LR-01) appears to lie on the boundary between two distinctive colluvial units. The colluvial deposits are situated below very steep ($>50^\circ$) natural terrain forming the summit of Lion Rock and are likely to represent debris fan aprons. The boulders may reflect rockfalls from Lion Rock itself. However, neither the relative ages of emplacement of the boulders nor their exact sources could be confidently determined, although the lithology of the boulders is the same as that forming the upper cliffs of Lion Rock.

Samples were collected at elevations between 176 and 208 mPD from the uppermost central portions of the boulders, and from rock faces inclined between 14° and 32° . A small portion of the upper face of LR-01 is covered by colluvium No. 3 (Fig. 6),

which also appears to wrap around the boulder to the east, suggesting that LR-01 predated deposition of colluvium No. 3.

Fei Ngo Shan

In eastern Kowloon, three very large (5–10 m diameter) boulders (Table 1) within a single large colluvial unit below the southwest flanks of Fei Ngo Shan (Fig. 7) were sampled. The boulders are composed of block bearing coarse ash crystal tuff, similar to that forming the upper cliffs of Fei Ngo Shan, although the exact source of detachment could not be located. The three boulders were sampled at approximately the same elevation (158–162 mPD). Samples were taken from the uppermost central portions of the boulders, from rock faces inclined between 8° and 30° .

Deep-Seated Scarp Sites

Lai Cho Road

Samples were collected from a large composite natural terrain escarpment above Lai Cho Road, in western Kowloon

Figure 5. Geomorphological features, sample locations, and dating results for the Ap Lei Chau landslide site. Legend as for Figure 2.

(Fig. 1), featuring two clearly defined steep scarps (A1 and A2 in Fig. 8) with sharp lateral boundaries. The escarpment is underlain by coarse-grained granite and is located above a recently formed major cut-slope. Neither of the two scarps is associated with recognizable debris lobes, and man-made excavations have probably removed these. Three samples (LCR-01, LCR-03, and LCR-04, Table 1) were taken from the northern and southern flanks of the smaller (A2) scarp, close to the intersection with the A1 scarp, whereas one sample (LCR-02) was taken from the A1 scarp, 10 m southwest of this intersection (Fig. 8). Samples were collected from 3 m deep rock scarp surfaces inclined at 36° to 45° , and at elevations varying from 109 to 111 mPD. Based on aerial photograph interpretation, the A2 scarp truncates the A1 scarp and therefore is younger.

Mid-Levels

The Mid-Levels landslide comprises a prominent natural terrain landslide feature with a single well-defined 5 m deep main scarp, located immediately northwest of Victoria Peak on Hong Kong Island (Fig. 1). The scarp lies at an elevation of ~ 400 mPD (Fig. 9). Although the ground immediately below the Mid-Lev-

els scarp is moderately sloping, no directly associated landslide debris was identified downslope from the scar.

Five samples were collected for exposure dating from the main scarp area (Fig. 9). All of the samples were collected from relatively steep (60° – 80°) faces, mostly at 3 m or greater below the inferred original rock surface. One sample (ML-04) was collected within less than 3 m of the inferred prefailure land surface to test for possible inheritance.

ANALYTICAL METHODS

Sample preparation was carried out at the Australian National University and followed established protocols (Barrows et al., 2001). All exposure ages are calculated conventionally assuming no significant erosion since initial exposure. We used a ^{10}Be production rate of 5.1 and a ^{26}Al production rate of 31.1 atoms/g/yr (Stone, 2000). The isotope ratios of $^{10}\text{Be}/\text{Be}$ and $^{26}\text{Al}/\text{Al}$ were measured by accelerator mass spectrometry on the 14UD accelerator at the Australian National University (Fifield et al., 1994). Production rate calculations and ages for ^{10}Be and ^{26}Al respectively are presented in Tables 2 and 3.

Figure 6. Geomorphological features, sample locations, and dating results for the Lion Rock landslide site. Legend as for Figure 2.

Figure 7. Geomorphological features, sample locations, and dating results for the Fei Ngo Shan landslide site. Legend as for Figure 2.

Figure 8. Geomorphological features, sample locations, and dating results for the Lai Cho Road landslide site. Legend as for Figure 2.

RESULTS

Deep-Seated Scarp and Debris Lobe Sites

Sham Wat Debris Lobe

The five ^{10}Be exposure ages (Table 2) from the scarp/source area of the main lobe (Fig. 2) range from 19.7 ± 2.2 ka to 38.0 ± 5.2 ka. The five exposure ages from blocks on the debris lobe are much more variable, ranging from 33.1 ± 3.0 ka to 285 ± 23 ka. A single exposure age using ^{26}Al (283 ± 36 ka) (Table 3) was also obtained on one sample (SWD-07). This is in good agreement with the ^{10}Be age (285 ± 23 ka), indicating no significant burial history. The oldest exposure age (285 ± 23 ka) is interpreted as providing a minimum apparent age for the original ground surface. The youngest exposure age falls within the range of the four exposure ages from the scarp. A normalized X^2 test on these five exposure ages is consistent with a single population with dispersion in the data due to random errors ($X^2 = 1.34$). The weighted mean for this population

is 32.3 ± 5.4 ka and provides the best estimate for the age of the landslide.

Sunset Peak West

Three exposure ages (Table 2) from the scarp/source area of the landslide (Fig. 3) range in age from 9.1 ± 1.1 ka to 7.4 ± 1.1 ka. The youngest sample (7.4 ± 1.1 ka) was collected from the base of the main scarp, well below (>3 m) the reconstructed original rock surface. This is unlikely to preserve an inherited cosmogenic signature from prior to the landslide. Another sample (TCR-04) from the eastern flank has a similar age (7.7 ± 2.9). The oldest age (9.1 ± 1.1 ka) comes from a sample (TCR-02) on the upper part of western flank of the scarp, closer to the former rock surface, and is therefore more likely to include some inheritance. A sample from the rock surface adjacent to the main scarp (TCR-03) provides a minimum age of the original land surface prior to slope failure (70.7 ± 6.0 ka). The three other samples from the scarp/source area are likely to come from a single population ($X^2 = 0.63$), with a mean age of 8.2 ± 0.9 ka.

Figure 9. Geomorphological features, sample locations, and dating results for the Mid-Level landslide site. Legend as for Figure 2.

TABLE 2. ^{10}Be EXPOSURE AGES

Sample	Lab code	^{10}Be ($\times 10^3 \text{ g}^{-1}$)	Production rate ($\text{g}^{-1}\text{yr}^{-1}$)	Age (ka)
<u>Deep-seated Scarps and Debris Lobes</u>				
<u>Sham Wat Debris Lobe</u>				
SWD-01	ANU-M234-19	148 ± 15	4.0	37.1 ± 4.5
SWD-02	ANU-M226B-07	151 ± 18	4.0	38.0 ± 5.2
SWD-03	ANU-M234-10	111 ± 18	4.2	26.3 ± 4.6
SWD-04	ANU-M224B-30	80 ± 7	4.1	19.7 ± 2.2
SWD-05	ANU-M234-09	119 ± 18	4.4	27.3 ± 4.5
SWD-06	ANU-M234-05	120 ± 7	3.6	33.1 ± 3.0
SWD-07	ANU-M234-06	973 ± 36	3.6	285 ± 23
SWD-08	ANU-M224-26	926 ± 41	3.5	281 ± 23
SWD-09	ANU-M224-27	762 ± 35	3.5	227 ± 19
SWD-10	ANU-M226B-08	376 ± 19	3.7	103 ± 8.9
<u>Sunset Peak West</u>				
TCR-01	ANU-M224-25	31 ± 4	4.2	7.4 ± 1.1
TCR-02	ANU-M226B-05	38 ± 4	4.1	9.1 ± 1.1
TCR-03	ANU-M224-24	328 ± 16	4.7	70.7 ± 6.0
TCR-04	ANU-M233-09	33 ± 12	4.3	7.7 ± 2.9
TCR-05	ANU-M234-15	845 ± 29	3.9	227 ± 18
TCR-06	ANU-M233-10	1072 ± 37	4.0	284 ± 22
TCR-07	ANU-M224-30	163 ± 9	4.0	40.9 ± 3.7
TCR-08	ANU-M234-07	111 ± 6	4.1	27.3 ± 2.4
TCR-09	ANU-M226B-06	60 ± 5	4.0	15.1 ± 1.6
TCR-10	ANU-M234-08	210 ± 21	4.1	52.1 ± 6.4
<u>Tsing Yi</u>				
TY-01	ANU-M233-02	170 ± 9	3.6	47.7 ± 4.1
TY-02	ANU-M225-05	170 ± 8	3.6	47.3 ± 4.0
TY-03	ANU-M233-03	129 ± 7	3.7	35.3 ± 3.1
TY-04	ANU-M233-20	159 ± 7	3.6	44.8 ± 3.7
TY-05	ANU-M225-04	34 ± 4	3.1	11.0 ± 1.6
TY-07	ANU-M233-04	181 ± 8	3.8	48.5 ± 4.0
<u>Ap Lei Chau</u>				
ALC-01	ANU-M234-13	271 ± 15	3.8	72.7 ± 6.4
ALC-02	ANU-M225-12	41 ± 5	3.7	11.1 ± 1.6
ALC-03	ANU-M234-14	263 ± 19	3.5	77.6 ± 7.8
ALC-04	ANU-M225-09	40 ± 7	3.7	10.8 ± 2.2
<u>Rock and Boulder Falls</u>				
<u>Lion Rock</u>				
LR-01	ANU-M225-08	15 ± 2	3.9	3.7 ± 0.4
LR-02	ANU-M225-07	15 ± 2	3.9	3.8 ± 0.5
LR-03	ANU-M233-19	9 ± 2	3.9	2.3 ± 0.4
<u>Fei Ngo Shan</u>				
FNS-01	ANU-M233-16	220 ± 13	3.8	58.8 ± 5.3
FNS-02	ANU-M225-03	229 ± 14	3.8	60.4 ± 5.5
FNS-03	ANU-M233-17	208 ± 11	3.9	54.7 ± 4.8
<u>Deep-Seated Scarps</u>				
<u>Lai Cho Road</u>				
LCR-01	ANU-M224-30	20 ± 3	3.2	6.4 ± 1.1
LCR-02	ANU-M233-07	19 ± 2	2.6	7.5 ± 1.0
LCR-03	ANU-M224B-27	21 ± 3	3.2	6.5 ± 0.9
LCR-04	ANU-M233-08	15 ± 2	2.9	5.0 ± 0.9
<u>Mid-Levels</u>				
ML-01	ANU-M234-02	23 ± 6	3.9	6.0 ± 1.6
ML-02	ANU-M224B-28	27 ± 4	3.8	7.0 ± 1.2
ML-03	ANU-M234-03	31 ± 5	4.0	7.7 ± 1.3
ML-04	ANU-M224-29	134	3.5	<38
ML-05	ANU-M234-04	29 ± 4	3.6	8.2 ± 1.2

TABLE 3. ^{26}Al EXPOSURE AGES

Sample	Lab code	Al (ppm)	^{26}Al ($\times 10^3 \text{ g}^{-1}$)	Production Rate ($\text{g}^{-1}\text{yr}^{-1}$)	Age (ka)
TCR-05	ANU-M237-21	211 $\pm$ 11	5211 $\pm$ 624	23.9	246 $\pm$ 34
TCR-06	ANU-M237-19	176 $\pm$ 9	5545 $\pm$ 733	24.6	255 $\pm$ 38
TY-04	ANU-M237-16	93 $\pm$ 5	867 $\pm$ 249	21.8	40.5 $\pm$ 12
SWD-07	ANU-M237-17	522 $\pm$ 26	5485 $\pm$ 590	22.2	283 $\pm$ 36
ALC-03	ANU-M237-20	155 $\pm$ 8	1352 $\pm$ 783	21.1	66.3 $\pm$ 39

Four large boulders, protruding from the debris lobe of the landslide have exposure ages (Table 2) ranging from 15.1 $\pm$ 1.6 ka (TCR-09) to 284 $\pm$ 22 ka (TCR-06) (Fig. 3). The two oldest ages (227 $\pm$ 18 ka and 284 $\pm$ 22 ka) came from samples taken from opposite ends of the same block (TCR-05 and TCR-06 respectively). The independent exposure ages using ^{26}Al (246 $\pm$ 34 ka and 255 $\pm$ 38 ka) (Table 3) for these samples are in very good agreement with the ^{10}Be exposure ages and indicate no significant burial. The two youngest ages from the debris lobe (27.3 $\pm$ 2.4 and 15.1 $\pm$ 1.6 ka) also come from two samples (TCR-08 and TCR-09 respectively) from the same block. The two remaining blocks have intermediate exposure ages (40.9 $\pm$ 3.7 ka [TCR-07], 52.1 $\pm$ 6.4 ka [TCR-10]). The difference between the paired ages from the same blocks, the range of ages between the four blocks, and the much younger ages from the scarp face, together indicate significant inheritance of cosmogenic isotopes in these blocks from previous exposure. The shallow nature of this landslide means that much of the material was probably sourced from close to the original rock face. The oldest exposure age (284 $\pm$ 22 ka) provides a minimum age for this original surface. The mean age from the source area (8.2 $\pm$ 0.9 ka) provides the best estimate for the age for the landslide.

Tsing Yi

The two boulders (TY-01 and TY-02) within the DL4 debris lobe have almost identical exposures ages (Table 2) of 47.7 $\pm$ 4.1 ka and 47.3 $\pm$ 4.0 ka, respectively (Fig. 4). A sample from the third boulder (TY-03), within the adjacent CL1 debris, has a younger exposure age of 35.3 $\pm$ 3.1 ka. The two samples (TY-04 and TY-07) from the SJ1 cliff have exposure ages of 44.8 $\pm$ 3.7 ka and 48.5 $\pm$ 4.0 ka, respectively (Table 2). A duplicate of sample TY-04 was also analyzed for ^{26}Al (Table 3). This gave an exposure age of 40.5 $\pm$ 12 ka, agreeing with the ^{10}Be exposure age. A sample (TY-05) from the SJ2 cliff has an exposure age of 11.0 $\pm$ 1.6 ka (Table 2).

The exposure ages for the Tsing Yi site are remarkably consistent and indicate that most of the debris in the DL4 debris lobe was derived from the SJ1 escarpment (Fig. 4). The five exposure ages from SJ1 and DL4 are very likely to be from a single population ($X^2 = 0.18$), with a mean age of 47.0 $\pm$ 1.6 ka. A single outlier, represented by a boulder age of 35.3 $\pm$ 3.1 ka (TY-03), suggests that this boulder may have fallen more recently from the cliff. Alternatively, this boulder may have

rolled during its exposure history. The younger exposure age for SJ2 (11.0 $\pm$ 1.6 ka) indicates a more recent landslide/rockfall event from this source area.

Ap Lei Chau

The sample from the highest face (ALC-02) gave the youngest exposure age (11.1 $\pm$ 1.6 ka) (Fig. 5; Table 2). This age closely matches the exposure age of the sample from the boulder (ALC-04, 10.8 $\pm$ 2.2 ka) (Table 2), indicating that it is the likely source area for that debris. Together, these two ages are very likely to record the same event ($X^2 = 0.01$) with a mean age of 11.0 $\pm$ 1.3. The sample on the eastern edge of the main scarp (ALC-01) and the sample from the adjacent scarp feature (ALC-03) gave similar exposure ages of 72.7 $\pm$ 6.4 ka and 77.6 $\pm$ 7.8 ka (Table 2). The ALC-03 sample also gave an exposure age of 66.3 $\pm$ 39 ka using ^{26}Al (Table 3), which overlaps the ^{10}Be exposure age. There is no evidence of debris below the ALC-03 scarp feature, which is very degraded and poorly defined on aerial photographs.

Rock and Boulder Fall Sites

Lion Rock

The ages indicate that the boulders were all detached from their source areas within the past 4000 yr. Two samples (LR-02 and LR-03) on the same colluvial unit gave exposure ages of 3.8 $\pm$ 0.5 ka and 2.3 $\pm$ 0.4 ka, respectively (Table 2). The third sample (LR-01) within an adjacent unit gave an age of 3.7 $\pm$ 0.4 ka (Table 2). The exposure ages of LR-01 and LR-02 overlap, and although the boulders appear to have detached from slightly different source areas on Lion Rock, they appear to have done so at approximately the same time. This is likely to represent the best estimate for the timing of a major boulder fall event. Boulder LR-03 (2.3 $\pm$ 0.4 ka) probably represents a separate, more recent, rockfall.

Fei Ngo Shan

All three boulders gave virtually identical exposure ages, within 1 σ error (Table 2). Sample FNS-01 gave an age of 58.8 $\pm$ 5.3 ka, whereas samples FNS-02 and FNS-03 have exposure ages of 60.4 $\pm$ 5.5 ka and 54.7 $\pm$ 4.8 ka, respectively. The three exposure ages are likely to constitute a single population ($X^2 = 0.34$), with a mean age of 57.7 $\pm$ 3.0 ka. Due to the complexity and general degradation of the upper flanks of Fei Ngo Shan, the source of the boulders is uncertain. However, the identical lithology of the boulders and absolute age data suggest that the large boulders probably fell together, or within a short period of each other, from the same source area.

Deep-Seated Scarp Sites

Lai Cho Road

The three exposure ages from the smaller A2 scarp range from 6.5 $\pm$ 0.9 ka to 5.0 $\pm$ 0.9 ka (Table 2). It is likely that these three ages constitute a single population ($X^2 = 0.83$) with a mean

age of 5.9 ± 0.8 ka. The exposure age from the larger scarp is 7.5 ± 1.0 ka, suggesting that this feature is slightly older than the smaller scarp. However, two ages from the smaller landslide scarp overlap the age from the larger scarp. This raises the possibility that both scarps were formed during a single event ($X^2 = 1.2$). The weighted mean for these four ages is 6.3 ± 1.0 ka, which gives the best age estimate for a single landslide.

Mid-Levels

Aside from one sample (ML-04) that did not run well, the remaining four exposure ages (Table 2) group closely between 6.0 ± 1.6 ka (ML-01) and 8.2 ± 1.2 ka (ML-05). These four ages probably constitute a single population ($X^2 = 0.47$), with a mean age of 7.4 ± 1.0 ka. Therefore, this is our best estimate for the age of this landslide.

DISCUSSION

The exposure ages reported here provide the first direct estimates of the timing of landscape evolution by landsliding in Hong Kong. They reveal a history of deep-seated landsliding dating back at least 50,000 yr, which may be the upper limit for recognition of such features in the Hong Kong weathering environment. The largest landslide event occurred ca. 32,000 yr ago and entailed deposition of some 1,000,000 m³ of debris almost to sea level. Rock and boulder falls involving “mega-scale” boulders have also been active in the evolution of the Hong Kong landscape. The exposure ages suggest that such events have occurred sporadically between ca. 57,000 and ca. 2000 yr ago. There is potential evidence in debris from two of the deep-seated landslides studied of ancient landscape surfaces in Hong Kong that are at least 280,000 yr old. The exposure ages have provided important validation of the relative chronology identified from aerial photograph interpretation, particularly in areas where clusters of relict natural terrain landslides are observed. Overall, this study has demonstrated the successful application of cosmogenic nuclide analysis using ¹⁰Be and ²⁶Al to the dating of landslides in Hong Kong from a few tens of thousands of years down to only a few thousand years, despite low production rates because of low latitude and low altitude.

Deep-Seated Scarps and Debris Lobes

For the scarp and debris lobe sites, we generally found poor agreement between exposure ages in the debris and the scarp areas. The wide range of ages from the debris lobes at the Sham Wat Debris Lobe and Sunset Peak West sites indicates that much of the surface of these lobes is composed of material that was derived from levels that were close to the ground surface before the landslide. Intriguingly, at both sites there is an increase in boulder age with distance from the scarp, suggesting that the main mode of failure was by large-scale debris avalanche. This corroborates the findings of King (1998) at the Sham Wat site, who proposed that the landslide incorporated considerable fine

material from the weathered profile to form a slurry flow that emplaced boulders of up to 20 m³, far from their source. Multiple samples were required from the scarp to identify the depth of the former land surface, whereas multiple samples were required from the debris lobes to identify blocks with inheritance. At both sites, the most consistent, and presumably most reliable, ages for the landslide came from the scarp face, with the unweathered scarps providing the best ages to constrain the landslide.

At the Sham Wat Debris Lobe, the samples along the scarp face were collected at slightly different elevations, but all were from more than 2.5 m below the crest of the scarp. Sample SWD-04 gave a relatively young age of 19.7 ± 2.2 ka, and we strongly suspect that this rock surface spalled sometime after the landslide. The age of ~32,000 yr for the Sham Wat Debris Lobe is comparable to the 35,000 yr age reported by King (2001), based on standard optically stimulated luminescence dating methods. The surface exposure ages strongly suggest that the landslide occurred as a single large event rather than as a result of multiple smaller events. None of the surface exposure ages reported here and elsewhere (Sewell and Campbell, 2005) suggest a significant transport event for the Sham Wat Debris Lobe within the last 10,000 yr, as proposed by Murray (2001) on the basis of the dose distribution luminescence dating method.

At the Sunset Peak West landslide site, the depth of the former land surface was investigated by collecting three samples from the scarp surface at slightly different depths in relation to the crest of the scarp. A sample from a rock surface adjacent to the main scarp was also analyzed to test whether this surface could have formed at the same time as the main scarp. The results from the scarp surface for Sunset Peak West showed a slight increase in age from the deepest to the shallowest, indicating that the latter samples are likely to include some inheritance. Despite the presence of some inheritance, the mean exposure age (8.2 ± 0.9 ka) for the three samples from the scarp/source area provides the best estimate for the age for the landslide. The exposure age of the adjacent rock surface indicates either that it was very shallow before the landslide or that it represents a much older surface. It is intriguing that the oldest exposure age (284 ± 22 ka) in debris at the Sunset Peak West landslide is similar to that of debris in the Sham Wat Debris Lobe. Thus, there is potential evidence from two of the sites for ancient landscape surfaces in Hong Kong of at least 280,000 yr old (i.e., surfaces of this age will have been weathered and come into equilibrium with the “erosion” rate).

Owing to the substantial degradation of the scarp/source area at the Tsing Yi landslide site, it was uncertain which scarp surfaces contributed to the various debris lobes, even after meticulous aerial photograph study. Therefore, multiple samples were collected from the debris lobes, as well as from the overlooking sheeted rock surfaces, in an attempt to identify (1) the timing of the landslide event (or events) and (2) the possible source areas of the debris using the surface exposure ages. The detailed interpretation of aerial photographs, which permitted accurate delineation of the debris lobes, provided invaluable

assistance in the selection of the samples sites. The exposure ages reveal unequivocally that most of the debris was derived from the nearest sheeting joint escarpment (SJ1) during a single event ca. 47,000 yr ago, and that a more recent landslide event occurred from the adjacent SJ2 escarpment at ca. 11,000 yr ago. The Tsing Yi site is the oldest deep-seated landslide feature successfully dated in this study with a definable scarp area and debris lobe. An age of 50,000 yr may be close to the upper limit for recognition of such features in Hong Kong by aerial photograph interpretation.

Despite a clearly defined main scarp and debris lobe identified from aerial photographs, the Ap Lei Chau landslide yielded only two suitable rock surfaces for exposure dating in the scarp area, and only one suitable boulder surface in the debris. Therefore, an additional sample was collected from an adjacent, very degraded scarp to test (1) the relative age determined from aerial photograph interpretation and (2) whether this scarp recorded a much older landslide event. Our results have yielded excellent agreement between the scarp and boulder exposure ages, and indicate that the Ap Lei Chau landslide scar has been well preserved over the past 11,000 yr. Not surprisingly, the adjacent, highly degraded scarp feature turned out to be considerably older.

Rock and Boulder Falls

The strategy at the sites of rockfall (Fei Ngo Shan and Lion Rock) was to sample large fallen boulders to determine (1) whether they were emplaced at the same time and (2) the relative age of surrounding colluvium. The application of cosmogenic nuclide exposure dating to these very large, generally tabular boulders was remarkably successful and was assisted by the availability of unobstructed, nearly horizontal surfaces suitable for sampling on the tops of the boulders. The geomorphology at both sites indicated that the boulder falls were not accompanied by emplacement of major colluvial lobes, and that the boulders either rolled, bounced, or slid into position, or combinations of all three mechanisms.

Exposure ages at the Fei Ngo Shan site reveal that the boulders most likely fell together, or within a short period of each other, suggesting that an exceptional trigger event (i.e., a seismic event) may have been responsible. The results from the Fei Ngo Shan site demonstrate the usefulness of dating clusters of large fallen boulders, even where there is little indication of the point of detachment. The well-correlated ages also suggest that the boulders were sourced from a relatively deep-seated failure, where inheritance was negligible.

The exposure ages at the Lion Rock site reveal that large isolated boulders have detached from the cliffs forming Lion Rock in the relatively recent past. Two of the boulders “within” one colluvial unit appear to have fallen at slightly different times (ca. 3700 and ca. 2300 yr ago). The exposure ages also indicate that the “host” colluvium is likely to predate both boulder fall events. A third large boulder “in” an adjacent colluvial unit is likely to have fallen at the same time as the 3700 yr old boulder,

suggesting that an exceptional trigger event (i.e., seismic event) may also have been responsible. The surface exposure ages from the three large boulders at the Lion Rock site are the youngest recorded in this dating study. They indicate that a rockfall event (or events) occurred between ca. 2000 and 4000 yr ago resulting in the emplacement of very large boulders on the slopes below Lion Rock.

Deep-Seated Scarps

The results from the Lai Cho Road and Mid-Level landslide sites demonstrate that apparent landslide scarp features can be reliably dated using cosmogenic isotopes, even where associated debris lobes are not preserved, and even though the scarps are relatively young (e.g., <10,000 yr). At both sites, the exposure ages obtained from various positions on the scarp surfaces are generally in good agreement.

At the Lai Cho Road site, exposure dating of an adjacent scarp has confirmed the relative age of an older and much larger landslide feature identified from aerial photograph interpretation.

CONCLUSIONS

This study has demonstrated that exposure dating using ^{10}Be and ^{26}Al can be successfully applied to dating of exposed rock surfaces associated with gravitational deformations such as large, deep-seated landslides, and rock and boulder falls. Exposure dating of the landslide scarp areas has produced the most reliable results.

In Hong Kong, well-defined ancient landslide features identified from aerial photograph interpretation and with scars greater than 20 m wide appear on the basis of exposure dating to be generally 1000s rather than 100s of years old. The maximum age of recognition by aerial photograph interpretation of these features in Hong Kong’s weathering environment may be ~50,000 yr, but more data are required to substantiate this. However, there is some potential exposure dating evidence of ancient landscape surfaces in Hong Kong at least as old as 280,000 yr. This indicates, perhaps surprisingly given Hong Kong’s present climate, that in some moderately steeply sloping parts of Hong Kong, the landscape has remained remarkably stable for long periods of time. However, it has also been subject to occasional large-scale failures. Whether such failures have been generated by extreme rainfall events, as are most present landslides in Hong Kong, and/or by other agencies, such as seismic events, as has already been alluded to in the case of the large rockfall events studied, remains to be established.

The findings in this study have direct relevance to natural terrain hazard studies carried out in Hong Kong in relation to areas of future development. Precise dating can provide reliable constraints on return periods for natural terrain landslides. The potential impact this might have on design of mitigation measures in the urban environment, however, requires considerably more investigation.

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