August, 2001

To: Juergen Herget
Sergei Parnachov
Paul Carling

From: Greg Balco

RE: Summary of cosmogenic-isotope analyses of material from Altai.

This is a summary of attempts to determine the age of large proglacial lake floods in the Katun and Chuja river valleys of the Altai Republic of Russia using exposure-dating techniques. These techniques are based on the cosmogenic radionuclide beryllium-10, which is produced by cosmic-ray bonbardment in quartz grains which are exposed to the cosmic ray flux near the Earth's surface. We analysed a series of samples from one eroded rock surface and four gravel dune fields, all of which were presumably created by the last major flood. I collected the gravel dune samples during fieldwork in Altai in 1999, and analysed them at the University of Washington during 2000 and 2001. Juergen Herget and Sergei Parnachov collected the rock surface sample in the summer of 2000; I analysed it in 2001, also at the University of Washington. We made the actual isotope ratio measurements by accelerator mass spectrometry at the Center for Accelerator Mass Spectrometry of Lawrence Livermore National Laboratories, Livermore, CA, USA.

1. ^{10}Be and ^{26}Al analysis of rock surface near Little Jaloman bar.

We analysed one sample of granodiorite taken from a rock pavement above the giant bar at Little Jaloman. According to Sergei and Juergen, who collected the sample, the rock pavement appeared to have been exposed and eroded by flooding; therefore, the exposure age of the sample should provide a date for the last episode of major flooding. The analytical data for this sample are as follows:

Table 1. Rock surface near Little Jaloman bar.

Sample	Project	Collected by	Processed by	Processing date
JH-1	Altai	J. Herget	G. Balco	June 15, 2001

SITE INFORMATION

Latitude	Longitude	Elevation (m)	Sample thickness	Shielding correction	(assumed) erosion rate (cm/yr)	(assumed) Rock density (g/cm3)
50.5150	86.5798	865	3.5	0.9932	0	2.7

ANALYTICAL DATA

$[^{10}Be]$ (atoms/g quartz)	+/-	$[^{26}Al]$ (atoms/g quartz)	+/-	$^{26}Al/^{10}Be$	+/-
1.838E+05	4.669E+03	1.118E+06	4.281E+04	6.1	0.28

SIMPLE EXPOSURE AGE (CORRECTED FOR PALEOMAGNETIC VARIATION)

^{10}Be age (yr)	^{26}Al age (yr)	Weighted mean of ^{10}Be and ^{26}Al ages
17000 +/- 1100	17100 +/- 1200	17100 +/- 800

The fact that the ^{26}Al and ^{10}Be ages are concordant suggests that the sample has a simple exposure history and the rock surface was not buried for a long period of time. The interpretation of these data is fairly simple. As long as the geomorphic interpretation of the site is correct, meaning that: 1) the surface was exposed and deeply eroded by flooding; 2) the surface was not covered by soil, sediment, or ice for a significant period of time since it was originally exposed; and 3) the surface has not eroded significantly since it was initially formed, these data give the age of the flood that created the surface.

2. ^{10}Be analysis of sediment samples from gravel bedforms.

2.A. Introduction to the technique.

We analysed a series of gravel samples from fields of large gravel bedforms at Platovo, Little Jaloman, Kuray, and Chuja. The purpose of these analyses was to try to directly date sedimentary features that were undoubtedly formed by the most recent large flood, rather than other features such as eroded rock surfaces (which may have been formed by glacial erosion or other unrelated processes and only slightly modified by flooding), or lake sediments (which can only provide bracketing ages for flood events). The chief problem with dating these features, and the reason there have not been very many efforts to date to apply exposure-age dating to sedimentary surfaces, is that sedimentary quartz contains ^{10}Be inherited from periods of exposure that predate the formation of the surface. Thus, an exposure age calculated from a single ^{0}Be measurement on sedimentary quartz will overestimate the age of deposition by an unknown amount.

Anderson et al. (1996) as well as Repka et al. (1997) proposed a strategy for separating inheritance from postdepositional exposure in dating sedimentary surfaces. It relies on the fact that the production rate of ^{10}Be (or ^{26}Al) varies in a known fashion with depth below the surface of a deposit, as follows:

$$P(z) = P_0 e^{-\frac{\rho z}{\Lambda}}$$

where $P(z)$ is the production rate (in atoms/g quartz) at depth z, P_0 is the production rate at the ground surface, ρ is the density of the sediment, and Λ is a constant (160 g/cm^3). If we can assume that the sediment was well mixed at the time of deposition, then the inherited ^{10}Be will be constant at all depths. If we then assume that the sediment has not been mixed or otherwise disturbed since deposition, then the concentration of ^{10}Be at any depth z, after a time t since deposition, is:

$$N(z,t) = N_{inherited} + tP_0 e^{-\frac{\rho z}{\Lambda}}$$

where $N(z,t)$ is the concentration of ^{10}Be in atoms/gram at depth z and time t, and $N_{inherited}$ is the concentration of ^{10}Be in the sediment at the time of deposition. This equation has two unknowns (t and $N_{inherited}$); therefore, if we analyse samples from two different depths in the deposit, we can solve for both of them and determine both the inherited ^{10}Be concentration and the time since deposition, as follows:

$$t = (N_0 - N(z))/(P_0 - P(z)) \text{ and } N_{inherited} = N(z) - tP(z) = N_0 - tP_0$$

In these formulae we have also ignored radioactive decay of ^{10}Be, which is not important for samples with total exposure histories < 100,000 yrs.

In theory, this technique should be ideal for dating the dunefields associated with the Altai megafloods. The presence of stratified bedforms indicates that the sediment within them was well mixed at the time of deposition, and the preservation of cross-bedding within the bedforms indicates that the sediment has not been mixed or otherwise disturbed since deposition; thus, both chief assumptions of the technique are met.

2.B. Sites.

We analysed samples from four sites (Table 2). The sample at Platovo came from the top of the riverside exposure near our campsite; all other samples were collected from pits dug into the tops of large dunes. The gravel surface at Platovo was covered entirely by 10 cm of organic-rich silt, with no evidence of mixing of gravel upwards into the silt cap. At Little Jaloman, Kuray, and Chuya, a surface layer of gravel overlies 5-15 cm of matrix-supported mixed gravel and silt, which in turn overlies clast-supported, crossbedded gravel. This stratigraphy appears to reflect gradual accumulation of windblown silt as well as some mixing of the surface gravel layer with the silt cap. This history, which somewhat violates the assumptions of our dating technique, could cause our model ages to slightly underestimate the true age of the surface; however, if mixing and accumulation are confined to only the upper ~10 cm, their effect is significantly less than analytical error.

Photos of the sample sites are attached as Appendix A.

We collected a fifth set of gravel samples, from the lower Kara-Kol dunefield, during the 1999 field season. This sample contained only quartz-poor lithologies, and we could not analyze it.

Table 2. Site locations and surface production rates for gravel dune samples.

Site	*Latitude*	*Elevation (m)*	*Shielding correction*	*Surface production rate for ^{10}Be (atoms/g quartz)*	*+/-*
Platovo	*52.0957*	*330*	*1.0000*	*7.1*	*0.42*
Little Jaloman	*50.4892*	*760*	*0.9948*	*10.3*	*0.61*
Kuray dunefield	*50.1847*	*1540*	*0.9989*	*19.3*	*1.14*
Chuya dunefield	*50.0885*	*1740*	*0.9996*	*22.5*	*1.32*

2.C. Sampling procedures.

Following the Anderson et al. method, each sample consisted of at least 25 individual gravel clasts, 2-5 cm intermediate diameter, collected from the surface or from a certain depth in a soil pit. The Anderson papers discuss, in some detail, the effect of the number of clasts collected on the likely accuracy of the age determination, and conclude that 30 clasts is the minimum number that will ensure that the sample is representative of the bulk sediment. At some sites I was not able to collect clasts of a single lithology. This may be a source of significant error in the results: clasts of different lithologies can be expected to come from different source areas, with different erosion rates and transport times, and therefore to have different average amounts of inherited ^{10}Be. If, for example, all the clasts collected at the surface were a different lithology than those collected at depth, it would violate the assumption that the two samples have the same amount of inherited ^{10}Be. Since at some sites the distribution of lithologies was different at the surface than at depth (perhaps due to different weathering rates and poor survival of some lithologies at the surface), it was not possible to collect monolithologic samples from each level (see Table 3). For those sites with varying lithologies, I tried to assemble the two samples to have equal proportions of different lithologies while maintaining a sufficient number of clasts. However, the use of multiple lithologies contributes significant uncertainty to the results, which I did not fully appreciate at the time of sampling. In future attempts to do this it is important to collect clasts of a single lithology for each pair of samples.

The majority of clasts that we collected at all four sites were dark-colored quartzite or silica-cemented sandstone or greywacke. Some lighter-colored quartzites were also common. The remainder of the clasts were igneous intrusives, primarily granite and granodiorite. When we assembled the bulk samples that were actually analysed for ^{10}Be, we combined material from individual clasts so that each clast contributed an equal amount of quartz.

Table 3. Lithology of clasts in gravel dunefield samples.

Sample location and name	Sample depth	Clast lithology: dark green, gray, and red quartzites	Light gray, clean quartzite	unidentified dark metaseds.	Calcareous sandstone	Plutonic	Total clasts
CHUYA BASIN							
C-0	Surface	17			7	14	38
C-50	50 cm	23				4	27
KURAY BASIN							
K-0	Surface	8	15	5			28
K-50	70 cm	12	18				30
LITTLE YALOMAN DUNEFIELD							
Pit 1							
LY-1-0	Surface	25					25
LY-1-50	50 cm	35					35
Pit 2							
LY-2-0	Surface	47					47
LY-2-50	50 cm	39					39
PLATOVO DUNEFIELD							
PL-0	Surface	29					29
PL-75	75 cm	33					33

2.D. Chemical preparation methods.

The fine-grained, impure quartzite common in these gravel samples caused one additional problem. Normally, we extract ^{10}Be and ^{26}Al from quartz simultaneously using HF dissolution and a column chromatography procedure to isolate the various metals. This procedure only works on extremely pure (> 99.9%) quartz. Because of the fine-grained nature of the samples, the usual techniques for purifying quartz were unsuccessful and we were unable to obtain quartz of this purity. Thus, we were forced to develop a new procedure: first, we added ^{9}Be carrier and dissolved the sample (which usually consisted of ~90-98% quartz) in HF, then evaporated the resulting SiF_4, yielding ~1-2 g of fluoride precipitate. We extracted Be from this residue by a method involving fusion with KHF_2 and Na_2SO_4, which has been described by Stone (1998). This procedure does not allow extraction of ^{26}Al.

We tested this modified method by measuring both process blanks and replicates of several samples. Our average process blank (of three analyses, excluding ^{10}Be already present in the ^{9}Be carrier) had 230 +/- 12,500 atoms ^{10}Be, an insignificant amount. Replicate analyses of samples LY-2-0, LY-2-50, PL-0, and PL-75 agreed within error, although replicate analyses of LY-1-0 differed significantly (Table 4). In the latter case one of the analyses had very high analytical error due to poor AMS performance on an extremely small sample, and we therefore disregarded it. Several other samples gave poor AMS beam currents: this appeared to be the result of incomplete recovery of Be in the fusion process. These samples therefore yielded very small Be targets for AMS analyis (down to 150 μg Be), which resulted in poor beam currents and limited beam time. This problem, which we corrected in later samples by adding more Be carrier (up to 350 μg), contributed significant (~ 10 %) analytical error for some samples.

2.E. Results.

TABLE4. ^{10}Be ANALYTICAL DATA.

Sample	Collected by	Processed by	Process date	[^{10}Be] (atoms/g)	+/-
C-O	GB	GB	5-Sep-2000	6.99E+05	1.66E+04
C-50	GB	GB	5-Sep-2000	6.52E+05	1.69E+04
K-0	GB	GB	5-Sep-2000	5.00E+05	1.92E+04
K-70	GB	GB	5-Sep-2000	3.53E+05	1.41E+04
LY-1-0-B	GB	GB	9-Aug-2000	2.35E+05	8.04E+03
LY-1-O-P	GB	GB	8-Sep-2000	1.63E+05	1.69E+04
	Note: LY-1-0-P disregarded on the basis of poor AMS performance.				
LY-1-50-P	GB	GB	8-Sep-2000	1.32E+05	2.54E+04
LY-2-0-A	GB	GB	1-Jun-2000	3.83E+05	1.04E+04
LY-2-0-B	GB	GB	9-Aug-2000	4.13E+05	1.38E+04
	Weighted mean of two analyses for LY-2-0:			3.94E+05	8.31E+03
LY-2-50-A	GB	GB	1-Jun-2000	8.16E+04	1.06E+04
LY-2-50-B	GB	GB	9-Aug-2000	7.09E+04	5.61E+03
	Weighted mean of two analyses for LY-2-50:			7.32E+04	4.96E+03
PL-0	GB	GB	5-Sep-2000	1.99E+05	7.28E+03
PL-0-P	GB	GB	8-Sep-2000	1.75E+05	1.40E+04
	Weighted mean of two analyses for PL-0:			1.94E+05	6.46E+03
PL-75	GB	GB	5-Sep-2000	1.11E+05	7.19E+03
PL-75-P	GB	GB	8-Sep-2000	1.17E+05	5.49E+03
	Weighted mean of two analyses for PL-75:			1.15E+05	4.36E+03

2.F. Interpretation.

2.F.1. Simple exposure ages. As discussed above, a simple exposure age, i.e. an exposure age calculated assuming zero inherited ^{10}Be, on a sedimentary deposit should yield too old an age due to the fact that there actually is inherited ^{10}Be in the sediment. However, this age does provide a maximum limiting age for the deposit: if the site has remained continuously exposed since the surface-forming event, the deposit cannot be older than the simple exposure age. Thus, the simple exposure ages calculated for each sample (Table 5) provide a maximum limit for the age of the flood that formed each set of gravel bedforms. The only exception to this could occur at the Kuray and Chuja sites where it is possible, though not likely, that the bedforms could have been formed by the drainage of one lake, then subsequently covered for a time by a later proglacial lake which did not drain catastrophically and remobilize the lake bed. If this were true, production of ^{10}Be would have been interrupted during the existence of the lake and the bedforms could be older than the simple exposure age; however, there does not appear to be any evidence that this could have happened.

TABLE 5. SIMPLE EXPOSURE AGE CALCULATIONS.

Assuming a gravel density of 2.1 g/cm^3.

Sample	*Simple exposure age (yr)*
C-O	*31300 +/- 700*
C-50	*56600 +/- 1500*
K-0	*26000 +/- 1000*
K-70	*46300 +/- 1800*
LY-1-0-B	*22900 +/- 800*
LY-1-50-P	*24800 +/- 4800*
LY-2-0	*38500 +/- 800*
LY-2-50	*13700 +/- 900*
PL-0	*27400 +/- 900*
Pl-75	*43600 +/- 1700*

With the exception of the anomalously young age from LY-2-50 (which is probably incorrect for reasons discussed in more detail later), these data indicate that the flood that created the large gravel dunefields must have taken place more recently than ~20,000 – 25,000 years ago. This conclusion agrees with radiocarbon and other dates on lacustrine sediments which suggest that both proglacial lakes and floods occurred at and after this time.

2.F.2. Depositional-surface model ages. Calculating exposure ages using both surface and deep samples from each site with the Anderson et al. depositional age model discussed above yields mixed results (Table 6).

First, the nature of the calculation and the poor precision of some of our analyses (discussed above) results in large errors in the model ages. This is an inherent limitation of the technique: the reliance on two depths only and the fact that analytical error for two samples is combined to yield the total error in the age estimate, means that these errors are likely to be large. The accuracy of the technique could be significantly improved by making measurements at more than two depths.

The errors reported in the table do not include uncertainty caused by the fact that the clasts we sampled represent a small sample from a random distribution. Anderson et al. conclude that for samples of 30 clasts, this source of error is likely to be less than 5%. It is impossible to quantify this error without making ^{10}Be measurements on a large number of clasts, which would be impractical. However, if only a few clasts in the sample had exposure ages much greater (~ 10x) than the average, they could potentially have a major effect on the accuracy of the ages. As discussed below, this source of potential error probably accounts for the inconsistent results of our model ages.

Second, in order to calculate these model ages we need to know the density of the sediment. Since we did not measure this directly (possibly Paul has measured this), I assumed a gravel density of 2.1 g/cm^3. Uncertainty in this value results in an error in the final age determination which is much less than the analytical errors reported in the table.

TABLE 6. SEDIMENT MODEL AGES CALCULATED FROM PAIRED SAMPLES

Disregarding radioactive decay and assuming gravel density of 2.1 g/cm^3.

Site	*Model age(yr)*	*Model inheritance (10^5 atoms/g)*
Chuja	*4300 +/- 2200*	*6.02 +/- 0.49*
Kuray	*12700 +/- 2000*	*2.56 +/- 0.4*
Little Jaloman - 1	*20700 +/- 5400*	*0.21 +/- 0.55*
Little Jaloman - 2	*64600 +/- 1900*	*-2.72 +/- 0.2*
Platovo	*17700 +/- 1700*	*0.68 +/- 0.12*

Third, one site (Little Jaloman, pit 2) yields impossible results. The difference in ^{10}Be concentration between surface and deep samples is larger than the difference in production rates – thus, the formula given above indicates an inheritance less than zero, which is impossible. At this location, one of the assumptions of the technique must have been violated – either vertical mixing of clasts has occurred, the site represents two separate episodes of deposition of clasts with different average ^{10}Be concentrations, or the samples do not accurately represent the average ^{10}Be concentration of the sediment. The last possibility, that one or more clasts in the surface sample had a significantly greater exposure age than the others, seems most likely.

The other four sites yield permissible results. Model ages from Platovo, Little Jaloman pit 1, and Kuray overlap within large error bounds. If these ages are correct, and the gravel dunes at all three of these sites were formed in the same flood, they indicate that the last flood in the Katun Valley took place near 16,000 - 17,000 years ago (the average of these three ages). This seems likely for two other reasons: first, the age from the gravel dunes at Platovo (17,700 yr) is probably the most reliable due to the relatively good analytical precision (not true of LY-1) and the fact that all of the clasts were the same lithology (not true at Kuray); and second, it agrees well with the age of the eroded rock surface near Little Jaloman that we discuss above.

The results from Chuya are more confusing. In contrast to the situation at LY-2 where the surface sample appeared to have excess ^{10}Be, the surface and deep samples at Chuya had very similar ^{10}Be concentrations, resulting in a very young model age of 4300 yr. This is unlikely to be the true age of the landforms for many reasons. Again, an age that is too young can be explained by two possibilities: first, the sediment may have been vertically mixed, or second, the deep sample may contain a few clasts with anomalously large exposure ages. Since this pit showed preserved cross-bedding, the second possibility is more likely.

We also calculated an inherited ^{10}Be concentration for each site. First, without considering the LY-2 and Chuya sites where we obtained anomalous ages, the data suggest inherited ^{10}Be of $<1 \times 10^5$ atoms/g at Platovo and Little Jaloman, and 2.5×10^5 at Kuray. This suggests that the upper basins were not the only source of sediment transported through the Katun Valley during floods (in which case we would expect the sediment at all three sites to have similar inherited ^{10}Be concentrations). Since the glaciers which flowed into the Katun Valley below Kuray could have contributed large amounts of fresh sediment with a low exposure age, this downstream decrease in the inherited ^{10}Be concentration of flood gravels seems reasonable, and does not appear to pose any problem in interpreting our data.

Again, the fact that the model ages at the Chuya and LY-2 sites appear to be wrong means that the inheritance estimates at these sites are also incorrect. However, we can use the inheritance data to examine what may have gone wrong at these sites. For example, assume that the problem at the Chuya site was caused by one or more anomalously old clasts in the deep sample, and that the average inherited ^{10}Be concentration at the site is actually the same as that measured at Kuray ($2.6 \pm 0.4 \times 10^5$). In this case the exposure age calculated from the surface sample would be 19,700 ± 2500 yr, which is similar to our other results. If we make a similar assumption at LY-2, that we measured anomalously old clasts in the surface sample and true inherited ^{10}Be in the sediment is similar to that measured at the adjacent LY-1 pit ($0.21 \pm 0.55 \times 10^5$), then the exposure age calculated from the deep sample is 9700 ± 12,000 yr, which, although a nearly meaningless number due to the very poor analytical accuracy of many of the samples involved, is at least not impossible. This does not account for the fact that the deep sample (LY-2-50) is anomalously "young" – to bring the data at this pit into line with the others we must also assume that there has been some mixing of gravel that has brought up deeper and less-exposed material, which seems less likely. Thus, although the calculations in this paragraph are pure speculation, it seems most likely that our technique failed at the LY-2 and Chuya sites because we inadvertently sampled anomalously old clasts in surface and deep samples, respectively. This underscores the most important problem with this technique, i.e. that it is difficult to take a representative sample of the clast population. In future attempts to use this technique I would prefer to sample many more clasts at each site.

3. Conclusions.

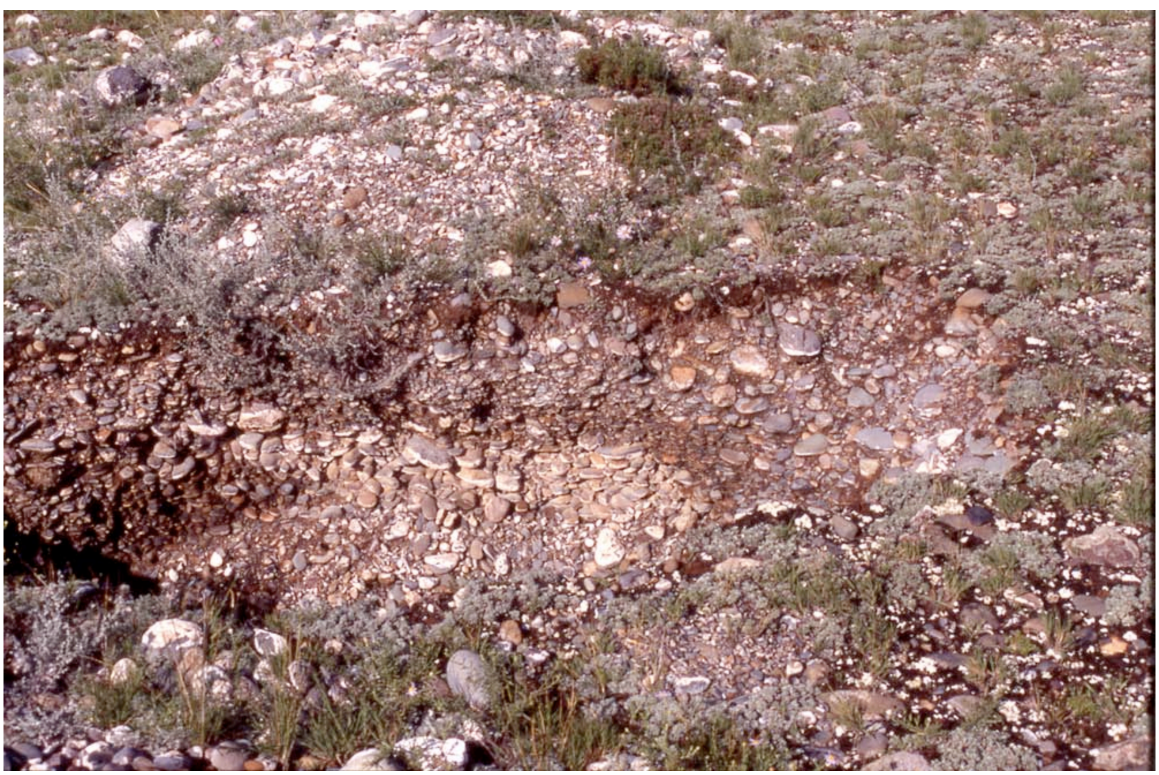
The attempts to directly date gravel bedforms suffered from poor analytical precision as well as inconsistent results that could not be explained by analytical error alone. However, age estimates from the sites where we did obtain reasonable results overlapped within large errors: these data, combined with the single direct exposure age on the rock pavement near Little Jaloman, indicate that the most recent major flood in the Katun Valley took place approximately 17,000 years ago.

Appendix A. Photos of cosmogenic-isotope sampling sites at gravel dune fields.

1. Gravel dunes at Platovo. Sampling site is near tents in background.

2. Sample site at Platovo.

3. Gravel dunes at Little Jaloman. Sampling sites at center left of photo.

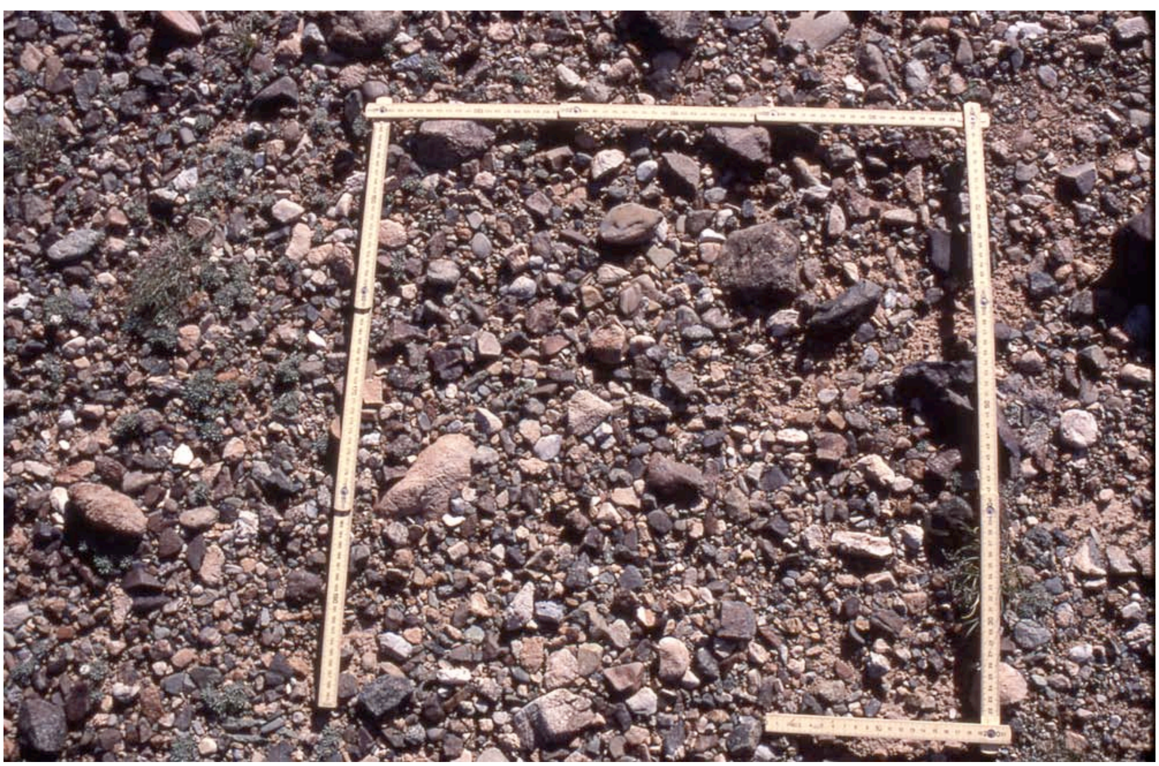


4. Pit 1 at Little Jaloman dunefield.

5. Kuray dunefield. Sampling site at center right of photo.

6. Sampling pit at Kuray dunefield.

7. Sample site at Chuja dunefield.



8. Surface gravel at Chuja site.

9. Sampling pit at Chuja site.