Revised Work Plan and Schedule

CRONUS-Earth Project

26 June 2004

Introduction

This document describes the work plan and research schedule for the revised Cosmic-Ray prOduced NUclide Systematics on Earth Project (CRONUS-Earth Project). The original objectives, methodology, and work plan were described in the CRONUS-Earth proposal submitted to the NSF on 15 July 2003. These will not be repeated here. The NSF has decided to fund the Project on the original time frame (5 years), but at a reduced budget ($10.6M reduced to approximately $5.8M). This document gives an overview of the changes in the scope of work that have resulted from this budget reduction. Detailed accounts of the change in scope of individual projects are given in the budget justifications accompanying the revised sub-project budgets.

Changes in the Scope of Work

Intercalibration and Standards

Numbers of intercalibration samples have been reduced by ~40% from the original proposal. Although there will be fewer analyses the fundamental intercomparison can still be successfully accomplished. It will however, limit the numbers of replicates and thus the precision with which results from different laboratories can be compared. It will also limit iterations on the comparison process in which laboratories improve their processing/analysis procedures and then repeat the comparison. In summary, the fundamental basis for utilization of results from a large number of laboratories will be established, but both the precision and the accuracy of the resultant data synthesis may be somewhat lower than had originally been intended.

Amounts of standard materials to be prepared will be reduced by ~20%. This will not affect utilization of standard materials within the CRONUS-Earth Project, but will reduce the period of time over which the materials can serve as a community standard after the Project is completed.

Laboratory-Determined Reaction Cross-sections

The originally-planned number of irradiations will be maintained. The incremental savings by reducing the number of samples exposed is small. Although not all originally-planned analyses will take place, unused targets will be archived and can be analyzed later if additional funding is obtained.

Analyses and cross-section calculations will be performed only for the “standard” nuclides (^{10}Be, ^{26}Al, ^{36}Cl, ^{14}C, and ^{21}Ne). Measurement of ^{53}Mn, ^{41}Ca, and ^{129}I targets has been dropped. The number of targets to be processed for the “standard” nuclides will be reduced by ~40%. Rather than focusing on the cross-section measurement project in the first 2 1/2 years of CRONUS-Earth (in order to provide useful results to the other Project components at an early point), it will be spread out over the entire 5 years. The first two years will focus on ^{10}Be and ^{26}Al, and years 3 and 4 and early year 5 on the remaining nuclides.

Dropping the measurements on ^{53}Mn, ^{41}Ca, and ^{129}I targets will have the effect of slowing the utilization of these nuclides by the community. Reducing the number of analyses of targets for the remaining nuclides will reduce the resolution with which the energy-dependence of the cross-sections can be determined. This may in turn reduce the robustness of the production-rate estimates, depending on the "smoothness" of the energy dependence.

Target Network Experiment

Both the number of latitude-elevation transects, and the resolution of those transects will be reduced. The water-target transects will be reduced from 5 altitudes at 7 different latitudes to 5 altitudes at 4 latitudes. The quartz-target transects will be reduced from 5 altitudes at 5 different latitudes to 4 altitudes at 3 latitudes. Furthermore, the experiments involving "exotic" target materials (brucite, boehmite, Al- and Mg-salts dissolved in water) have been eliminated, as have the high- and low-energy ^{36}Cl target experiments, inasmuch as these were considered higher risk.

The impact of reducing the number of targets will be to reduce the accuracy and precision of the estimation of spatial distribution of nuclide production. The amount of this reduction is difficult to calculate until at least preliminary results from the network are available. The elimination of the low-energy ^{36}Cl-targets limits the accuracy of the "energy-dependent" scaling factors, since the "low-energy" production relies now exclusively on the ^{32}P targets. The impact of eliminating the exotic target material experiments is that it will not be possible to directly determine the terrestrial production rate of ^{21}Ne from Mg and Al.

Cosmic-Ray Fluxes

The present-day cosmic-ray flux distribution will be determined using the global cosmic-ray neutron monitor network, supplemented with selected critical neutron measurements, and will be determined averaged over the past ~15 ka by measurement of saturated ^{14}C in slowly-eroding rock surfaces. The budget for the present-day flux determinations has been reduced by eliminating the measurement of the altitude dependence of low-energy neutron fluxes near the point of maximum cutoff rigidity (India). The experiments comparing measurements and models of neutron multiplicity in neutron monitors and the effects of shielding on neutron monitor response have also been eliminated; the project will instead rely on modeling calculations in these areas. In both cases the confidence in the flux-distribution estimates will be lowered by being forced to rely on modeling and extrapolation rather than experimental data.

The budget for the time-averaged neutron-flux determinations has been reduced by cutting the number of globally-distributed in situ ^{14}C samples to be analyzed from 250 to 150. This will reduce the robustness and precision of the estimated flux distribution.

Modeling and Synthesis

Reduction in the budget for this sub-project had to be achieved by cutting salary, since most of the original budget consisted of salary. This will result in fewer simulations and perhaps a lower level of model development. Impacts of these reductions are difficult to predict, but will probably include a slower approach of the physics-based models toward utility for earth-science applications. They may also include evaluation of fewer alternative explanations for observed phenomena and hence a weaker fundamental understanding of cosmic-ray produced nuclide production.

Web-based calculator

The reduced budget has been accommodated largely by cutting postdoctoral salary allotted to producing the Web-based calculator in the first two years of the project. Thereafter, revisions and upgrades to the calculator "framework" set up in the first two years will be made by undergraduate programmers, also saving salary costs. The essential fixed costs for this part of the project, covering MATLAB software and a dedicated server, are relatively minor and have not been affected by the budget reduction.

The main impact of the reduced budget on this portion of the project will be on the timetable for making the Web-based calculator available to the user community. Capabilities such as paleomagnetic correction of exposure ages and erosion rates will likely be deferred to the second or subsequent years of the project. Because we expect to write the code in a modular fashion, allowing us to extend its capabilities progressively, this will not delay initial release of a basic calculator for the most commonly-used nuclides (^{10}Be, ^{26}Al, ^{36}Cl, ^{3}He). We also note that some of the original functions and capabilities planned for the CRONNUS web-based calculator will be covered by the independent "i-CRONUS" project at the University of Arizona. We have initiated discussions with Marek Zreda on his plans and progress on the i-CRONUS project, to ensure compatibility and avoid duplication.

Geological Calibration

Reduced budgets were accommodated by reducing numbers of calibration sites and numbers of analyses to be performed at these sites. Total analyses (AMS and noble gas) were reduced from 1770 to 1125. Calibration sites were reduced from 20 to 10 or 11. Critical "primary" calibration sites were retained. The sites eliminated were secondary, "verification" sites, which were reduced from 16 to 5.

The purpose of multiple verification sites, and multiple analyses at each site was to enable rigorous quantification of the reliability of the production rate estimates and to provide rigorous uncertainty estimates. We feel that we can still provide greatly improved production rate parameters, but the quantification of uncertainty and reliability will necessarily be less well constrained.

Analyses and Sample Preparation

Analysis and sample preparation costs have been reduced by 58%. This directly reflects the reduction in the numbers of samples for the Laboratory Cross-section and the Geological Calibration sub-projects discussed above. The effects of these reductions have been discussed above.

Administration and Coordination

These costs were reduced by 35%. Ways that this was accomplished include cutting the number of workshops from 15 to 11. The full original number of annual CRONUS-wide workshops was retained; Steering Committee and focused workshops were cut from 10 to 6. The high-school outreach program in Seattle was reduced from 5 to 3 years duration.

The reduction in workshop support will lessen opportunities for focused attention to critical parts of the CRONUS methods and results; we will attempt to compensate through increased use of electronic communication and networking. The change in duration of the high-school outreach program will result in ~40% fewer students being affected.

Summary

Areas most strongly affected by the budget reductions are the Target Network Experiment, Modeling, and Geological Calibration. In general, items that were reduced in order to meet budget targets were some form of repetition of measurements (e.g, fewer secondary geological calibration sites, fewer Target Network latitude transects, fewer measurements at each site or transect). Given that a major part of the goals of CRONUS-Earth are to significantly improve the accuracy and reduce the uncertainty of production-rate estimates, numbers of data are of fundamental importance. The average reduction in numbers of samples analyzed across the entire Project is ~40%. Assuming an extremely simplistic Poisson statistics model, this would result in parameter estimates that are ~25% less precise than they would have been with the original number of samples. One of the early activities under the Project will be to develop a statistically-based model for parameter estimation. This model will be capable of providing much more rigorous estimates of the effects of changes in sample numbers and similar factors.

One of the stated goals of the original CRONUS-Earth proposal is to improve surface-exposure age estimates using cosmogenic nuclides anywhere on earth to the 5% accuracy level. The project members considered this goal to be a quite challenging one. Given the marked reduction in scope of the project, full achievement of this goal may no longer be realistic. However, we do still feel confident that the Project will be able to achieve its two major objectives: (1) a very significant improvement in the accuracy of surface-exposure ages based on cosmogenic nuclides, and (2) establishment of a consistent and well-founded approach to calculation of cosmogenic ages that will make results from throughout the community truly intercomparable. Additional funding at a later point might well make the 5% goal more feasible.

Project Timeline

Year 1

Intercalibration and Standards

Possible AMS standards will be identified and acquired and a methodology for blind tests and intercomparison drafted (Nishiizumi). Potential rock standards for AMS processing intercomparison will be investigated and reconnaissance samples collected (Bierman, Jull). For noble-gas preparation and analysis, a high-purity pyroxene standard with known concentrations of ^{3}He, ^{21}Ne, and ^{22}Ne will be purified from rock material. The Mg-concentration of each aliquot will be controlled by microprobe analysis (Mg is the dominant target element for ^{21}Ne and ^{22}Ne cosmogenic production) (Schaefer).

Laboratory Nuclear Reaction Cross-Sections

Pure target materials for irradiations will be obtained and compositions verified by chemical analysis (Caffee). Accelerator time will be obtained and scheduled. Irradiation apparatus will be constructed and installed on beamline. Initial irradiations (probably SiO_2 at LANSCE) will be performed. Processing of target materials will be initiated and short-lived products measured. Targets will then be retained until their activity has decreased enough that processing for AMS analysis can commence. [Later items in this list may not be accomplished until Year 2.] (Nishiizumi, Sisterson, Reedy)

Target Network Experiment

Target materials (^{3}H-free water and quartz) will be obtained for the noble-gas target experiments and tested. Target materials containers will be fabricated and tested. Extraction lines will be set up and tested at WHOI and LDEO. Blank values will be determined and intercompared at the two laboratories. A workshop will be held to decide sample-exposure locations and local contacts will be made. Initial emplacement of the first targets will be late in Year 1 or early in Year 2. (Kurz, Schaefer). Target materials for ^{32}P and ^{10}Be production will be obtained and purified. Extraction and analysis lines will be set up. (Zreda, Lal).

Cosmic-Ray Fluxes

The neutron monitor apparatus will be constructed and tested. (Zreda, Desilets). Modeling efforts will attempt to improve the accuracy in predicting the flux and spectra of primary galactic cosmic rays. Using space-craft/ balloon observations of primary spectra and a selected network of neutron monitor count rates the rigidity dependence parameterization of the heliospheric diffusion coefficients (solar modulation) will be optimized. Various atmospheric models describing the depth dependence of density and composition as a function of altitude using mainly balloon radiosonde data as a reference will be evaluated. (Clem, Desilets). A set of global samples for saturated ^{14}C analysis (mostly already collected by other investigators) will be identified and analysis of these samples will commence. (Lifton).

Geological Calibration

A workshop focused on specifics of calibration sample collection methodology and sampling protocol development will be held. The first sampling campaign will be conducted at the Bonneville Shorelines (Utah) with most project PI's participating. (Stone, Phillips) Sample analysis will be initiated. (Stone, Phillips, Nishiizumi). Components of portable drill rig will be purchased and assembled. (Farber).

Modeling and Synthesis

The statistically-based model for parameter estimation and identification of the sources of uncertainty will have the initial conceptual model formulation complete and the programming of the numerical model initiated by the end of the year. Model development will proceed in a sequential fashion, with repeated iterations to more comprehensive and sophisticated versions. (Borchers, Phillips). The Web-based ^{10}Be-^{26}Al-^{36}Cl-^{3}He exposure age/erosion rate calculator is expected to be up and running in time for the first annual CRONUS workshop, in summer 2005. Those attending will be encouraged to test this initial version prior to the meeting, a session will be devoted to user evaluations and feedback. Afterwards the calculator will be revised based on user feedback. (Stone, Balco).

The physics-based modeling effort will commence with updating the cross sections from various libraries that are available and testing them in benchmark calculations. This will be followed by generating comparisons between earlier model calculations and those with the updated formulations. (Masarik, Reedy).

Administration/Coordination

The first annual workshop of the Project will be held in December 2004. This workshop will focus on project organization and planning. A more detailed and refined project workplan will be formulated. Logistics will be planned and provided for the first field season. The first annual report will be compiled and synthesized. (Phillips).

Year 2

Intercalibration and Standards

A workshop will be organized, to include both CRONUS-Earth and the European Union CRONUS Project participants, on intercalibration and standard materials for AMS applications to TCN studies. AMS standards will be distributed to all US and European participants using the methodology described in the proposal and overseen by Prof. Marian Scott. (Jull, Nishiizumi). Based on the results from the first-year reconnaissance studies, the materials for AMS rock standards will be collected, processed, and purified. (Jull, Bierman). The purification and quality assurance of the noble-gas pyroxene standard will be completed. The standard will be distributed to all participating laboratories through Prof. Scott. (Schaefer).

Laboratory Nuclear Reaction Cross-Sections

First irradiations at LANSCE and Japanese accelerator will be completed and LANSCE irradiations of Ca and K targets will be performed. (Sisterson, Caffee). Processing of first-year targets will be completed and samples sent to AMS labs for analysis. (Nishiizumi, Lifton). Calculation of excitation functions can begin. (Reedy) Short-lived products from this year's irradiations will be counted and the targets retained until they have cooled down enough for further processing.

Target Network Experiment

Exposure of first/second year noble gas targets will continue. The second set of target containers will be fabricated, tested, filled, and transported to the exposure sites. (Kurz, Schaefer). The processing of the ^{32}P and ^{10}Be targets and their containers will be completed and the targets will be transported to the exposure sites. (Zreda, Lal).

Cosmic-Ray Fluxes

The energy-specific neutron counting campaigns with elevation will be conducted. (Zreda, Desilets). The models developed during the first year will be fine tuned in the second year. In addition, the angular dependence in the geomagnetic cutoff rigidity will be calculated for various site locations to determine the effect obliquely incident primary particles have on the neutron flux and spectra. FLUKA will also be used to calculate the expected depth dependence of spallation reactions through ~2 meters of rock considering various compositions. (Clem, Desilets). Analysis of saturated ^{14}C in rock samples will continue. (Lifton).

Geological Calibration

Effort devoted to geological calibration of nuclide production rates will peak in year 2. The four sites scheduled for sampling are: Western Scotland (in conjunction with CRONUS-EU participants), the Puget Lowland, Mauna Loa and the Breque site in the Peruvian Cordillera. These sites cover all major nuclides (^{10}Be, ^{26}Al, ^{36}Cl, ^{3}He, ^{21}Ne and ^{14}C). Results also spread over a wide range of latitude and altitude, which will allow us to begin testing scaling factors derived from the *in-situ* ^{14}C sub-project. (Stone, Phillips, Farber). Samples from the first-year sampling will be processed and analyzed. The portable drill rig will be completed and tested (Farber).

Modeling and Synthesis

The statistically-based model for parameter estimation and identification of the sources of uncertainty will be implemented. Emphasis will be on working with developers of the Web-based calculator to provide a version of the model that will be accessible to all project participants. The preliminary model will be employed to provide preliminary estimates of the sensitivity of the final products (ages) to estimated uncertainties of the parameters. These will be used to provide guidance for project strategy. (Borchers, Phillips). The second year of the Web-based Calculator sub-project will be devoted to extending the functions and capabilities of the basic calculator, and expanding the range of nuclides covered (e.g. to include ^{14}C and ^{21}Ne). Because the code will be written as a series of modules providing for increasingly complex calculations, the underlying code is not expected to have to change as capabilities such as paleomagnetic correction, prediction of depth-profiles, multiple-nuclide calculations, and so on are added on. Because the code will be written in a single, consistent "framework" in which to insert calibrated constants such as production rates, attenuation lengths, etc, the effort required to cover additional nuclides will be minimized.

The physics-based modeling will begin to incorporate new CRONUS-Earth data on particle-flux distributions. Based on this, efforts will focus on developing predictive capability for ^{10}Be and ^{26}Al in order to make comparisons with the geological calibration data beginning to come in. (Masarik, Reedy, Caffee).

Administration/Coordination

The second annual workshop will be conducted. This will focus on preliminary field results, approaches to final synthesis, and re-evaluation of project methods and goals. Logistics will be coordinated for four summer sampling campaigns. The second annual report will be compiled and synthesized.

Year 3

Intercalibration and Standards

The first batch of AMS rock sample preparation standards will be distributed through Prof. Scott. The second batch of AMS analytical standards will be distributed. Results from the initial distribution of standard materials will be collected, interpreted, and disseminated. (Jull, Schaefer, Nishiizumi).

Laboratory Nuclear-Reaction Cross-Sections

Neutron irradiations at LANSCE and Japan will continue. Short-lived products will be counted. Second-year targets will begin to be prepared for AMS analysis. Calculation of excitation functions will continue. (Caffee, Sisterson, Nishiizumi, Lifton Reedy).

Target Network Experiment

All targets will continue exposure. First batch of noble-gas target samples will be retrieved and analysis will commence. (Kurz, Schaefer).

Cosmic-Ray Fluxes

Neutron-flux measurements will be completed. Efforts will be redirected toward modeling muon contributions to neutron monitor data and modeling neutron multiplicity effects. (Zreda, Desilets). Saturated ^{14}C measurements will continue. (Lifton).

Geological Calibration

By this time we expect to have calibration data from all of the sites sampled in years 1 and 2, and we will be able to begin evaluating their mutual consistency. The last two "primary" calibration sites (Mt Mazama and sites on the Maine coast), and one additional site to be specified, will be sampled at this stage. (Stone, Phillips). A deep drill core will be collected from an equatorial site using the portable drill rig (Farber). The writing of papers on earlier results will be initiated.

Modeling and Synthesis

The parameter-estimation model work will focus on interaction with project participants to develop methods for quantifying uncertainties in all important parameters, and in particular for reconciling uncertainty estimates based on disparate approaches (e.g., production rates based on laboratory cross-section measurements versus those based on geological calibration samples). These will then be incorporated into the model. Results to date from the project will be employed as constraints for the model in order to test the model utility. (Borchers, Phillips). The new cross-section data set will be incorporated into the transport code libraries starting in year three. The production rates at the first two year's worth of field site will be retrospectively reanalyzed to determine the sensitivity of the models to the new cross-sections. Efforts will also focus on 3-D production scaling and evaluation of altitude/latitude scaling based on modeling. (Masarik, Reedy, Caffee).

Administration/Coordination

The third annual workshop will be conducted. This will focus on methodology for final synthesis of results. Logistics will be coordinated for four summer field campaigns. The third annual report will be compiled and synthesized.

Year 4

Intercalibration and Standards

A second workshop on intercalibration and standards will be organized. The second batch of AMS rock standards will be distributed. Data will be collected, compiled, and distributed within the Project from the earlier sets of rock and AMS standards.

Laboratory Nuclear-Reaction Cross-Sections

Final, high-energy irradiations will be conducted. As previously, short-lived products will be counted quickly and targets stored for processing for long-lived products. Efforts will shift toward the calculation of excitation functions. (Caffee, Sisterson, Nishiizumi, Lifton, Reedy). Preliminary excitation functions will be supplied to the parameter estimation model. (Borchers, Phillips).

Target Network Experiment

Noble-gas measurements will be completed on the first-year targets. The second-year targets will be retrieved and measured. Targets will be stored for tritium ingrowth. Preliminary estimates of spatial distribution of noble gases will be made. (Kurz, Schaefer). ^{10}Be and ^{26}Al targets will continue to be exposed. (Zreda, Lal).

Cosmic-Ray Fluxes

Modeling of multiplicity effects will be completed. (Zreda, Desilets). Saturated ^{14}C measurements will continue. (Lifton).

Geological Calibration

The major activity in year 4 is drilling of deep cores into stable surfaces in the Transantarctic Mountains, in order to calibrate production profiles due to muon interactions (Stone). Year 3 calibration samples will have AMS and noble-gas analysis completed. Secondary sampling campaigns will be conducted on Oregon basalt flows and one site to be determined. (Phillips, Stone, Farber). On completion of drilling and measurement of these samples we will be able to begin the synthesis of geologically-calibrated production rates for all of the major nuclides. Preliminary production rates will be calculated and delivered to parameter-estimation model. (Borchers, Phillips). Initial papers will be written and submitted on the results.

Modeling and Synthesis

Work will focus on employing the parameter-estimation/uncertainty model to rigorously intercompare results obtained from the various different approaches employed within the project and on preliminary attempts to identify causes of discrepant results and to reconcile them. This will culminate in a first attempt at "global" uncertainty analysis and parameter estimation for the entire project. (Borchers, Phillips). Using the physics-based model, the dependence of production rates on various parameters, such as geometry, geomagnetic field intensity , solar activity will be studied in detail using new experimental data obtained from CRONUS activities (cross sections, test samples measurements etc.). Numerical values for all important correction factors that must be considered in real sample treatment will be reported. (Masarik, Reedy, Caffee).

Administration/Coordination

The fourth annual workshop will be conducted. This will focus on intercomparison of results to date. Logistics will be coordinated for three summer field campaigns. The fourth annual report will be compiled and synthesized.

Year 5

Intercalibration and Standards

Statistical summary and analysis of all intercalibration work will be completed. Results will be factored into parameter estimation/uncertainty model. A paper for general use will be prepared and submitted, summarizing the results of the intercomparison project. A mechanism for making the remaining standard materials available to the community will be implemented. (Jull, Schaefer, Nishiizumi).

Laboratory Nuclear-Reaction Cross-Sections

Remaining target materials will be analyzed for long-lived products. Some target materials will be archived for possible additional analyses. Most work will go into calculation of final excitation functions and incorporation into parameter estimation model. (Caffee, Sisterson, Lifton, Reedy). Papers will be prepared and submitted on results.

Target Network Experiment

Tritium measurements will be conducted on all noble-gas targets. Final calculations of cross-sections and scaling factors from all noble-gas targets will be completed. (Kurz, Schaefer). ^{10}Be and ^{32}P targets will be retrieved, processed, and measured. Cross-sections will be calculated from these targets. (Zreda, Lal). All Target Network Experiment results will be synthesized and delivered to the parameter estimation model. Papers will be prepared and submitted on the results.

Cosmic-Ray Fluxes

The neutron-monitor data will be corrected using the multiplicity and muon modeling results. Attenuation lengths will be calculated and will be compared with experimental data from the Target Network Experiment. Effects of temporal variation in the geomagnetic field will be examined in detail. These results will be incorporated in the parameter estimation model. (Zreda, Desilets). Papers will be prepared and submitted on the results.

Geological Calibration

Final samples remaining from the Year 4 sampling campaigns will be analyzed. Final results from all geological calibration work will be evaluated for internal consistency and for consistency with parameters derived in other sub-projects. Geological calibration data is expected to provide “ground truth” in the final calculations synthesizing the results from all areas of the project. All data will undergo final vetting and re-examination. Effective cross-sections, depth-dependences, and production ratios will be calculated. Results will be delivered to the parameter-estimation model. (Stone, Phillips, Farber). Papers will be prepared and submitted on the results.

Modeling and Synthesis

The actual, final, synthesis, parameter value assignment, and uncertainty determination will be performed. The “public” model will be finalized and released. (Borchers, Phillips). Consensus results from the final data synthesis will be integrated into the Web-based calculator. (Stone, Balco). Complete theoretical multidimensional maps of all factors and transformation coefficients necessary for interpretation of real samples will be published based on the physical modeling. A user-friendly interface for potential users of cosmogenic nuclides in geosciences will be written. (Masarik, Reedy, Caffee).

Administration/Coordination

The fifth annual workshop will be conducted. This will be devoted to finalizing project results. The final project report will be completed. Final project publications will be coordinated. The most important and significant Project results will be synthesized into a single publication. This may take the form of a very large review paper (e.g. *Reviews of Geophysics*) or a bound report (e.g., AGU's *Geophysical Monographs*). This will contain both a summary of "final" parameter values and uncertainties and guidance to methodology in performing calculations using terrestrial cosmogenic nuclides. This will be accompanied by a formal "release" of user-friendly versions of accompanying software that can be employed to provide cosmogenic ages and erosion rates calculated in a flexible but consistent fashion. (All participants.)