Study of continental surface evolutions using *in situ*-produced cosmogenic ^{10}Be and ^{26}Al

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Cosmic rays, predominately neutrons which result from the interaction of primary cosmic rays (mostly protons and α particles) with Earth's atmosphere, continually bombard Earth's surface and induce nuclear transformations within the mineral lattice of exposed rocks. *In situ* ^{10}Be (half-life, $t_{1/2}$ = 1.5 Myr) is thus produced in the lithosphere by spallation of ^{16}O, ^{27}Al, ^{28}Si and ^{56}Fe, while most ^{26}Al ($t_{1/2}$ = 0.71 Myr) is produced at the Earth's surface through spallation of ^{27}Al, ^{28}Si and ^{56}Fe. The exponential attenuation of cosmic ray neutrons by matter limits such *in situ*-production essentially to the upper few meters of the Earth's crust. The accumulation of the *in situ*-produced cosmonuclides may therefore be used for quantitative examination of near-surface exposure histories. In specific cases, cosmogenic nuclide concentrations may be used to characterize and quantify chemical and physical processes involved in landform evolution and soil formations (Lal, 1991; Cerling and Craig, 1994). For such purposes, quartz appears to be the mineral of choice. An ubiquitous material, with a tight crystal structure minimizing diffusion and contamination by meteoric ^{10}Be transported in precipitation, its low content in aluminium - lower than few hundred ppm - facilitates in addition ^{26}Al measurements. Furthermore, its ^{16}O and ^{28}Si simple target chemistry is particularly well adapted to the use of *in situ*-produced ^{10}Be and ^{26}Al for studying surficial processes, the main targets for the ^{10}Be production at the Earth's surface being ^{16}O and ^{28}Si and ^{28}Si for the ^{26}Al production.

Erosion rate estimates

After sufficient exposure time ($t \gg [\varepsilon L^{-1}+\lambda]^{-1}$, where ε is the constant erosion rate (g cm^{-2} yr^{-1}), L the attenuation length (g cm^{-2}) and λ the radioactive decay constant (yr^{-1})), *in situ*-produced cosmogenic nuclide concentrations reach a steady-state with production balanced by erosional loss and radioactive decay. Long-lived cosmogenic ^{10}Be can reach steady-state concentrations for denudation rates ranging from few m.Myr^{-1} to hundreds m.Myr^{-1}. Assuming that erosion is a constant and continuous process, measured steady-state ^{10}Be concentrations have thus been extensively used to quantify average erosion rates of a variety of outcrops in various geologic and geomorphic settings.

This approach may also be applied at the scale of a watershed if one assumes that the cosmogenic nuclide content of sediment discharged by a river represents the average concentration, weighted for area and denudation rate of the various environments present, for the basin as a whole. This assumption is valid if erosion is sufficiently rapid (>5 m.Myr^{-1} for the case of ^{10}Be) that loss of cosmogenic nuclides is primarily through erosion rather than radioactive decay; if long-term (millennial scale) sediment storage is minimum; and, if the near-surface distribution of quartz is relatively uniform throughout the studied basin (Brown *et al.*, 1995). Providing that these conditions are fulfilled, stream sediment's cosmogenic nuclide concentration reflects average erosion rates over millennial timescales, whereas stream's sediment load reflects contemporary erosion rates. Comparison of these two erosion rates thus offers the possibility to quantify the erosional changes related to human activity. This technique may also allow by comparing erosion rates among various river basins to estimate the effects of climate, tectonics, lithology and topography on erosion rates.

Soil and landform development

Depth profiles of *in situ*-produced ^{10}Be and ^{26}Al in the upper few meters of the Earth's crust may be used to elucidate mechanisms involved in landform evolution and soil formations. Particularly, ^{10}Be distribution as a function of subsurface depth allows to unambiguously distinguish eroding surfaces from accumulating surfaces.

Although lateritic structures are present on about one third of the emerged continental areas, aspects of their genesis and evolution are controversial. In particular, questions remain regarding the origin of supergene materials (in situ versus external) and the relative effects of chemical and mechanical alteration. In addition, the occurrence and origin of quartz pebbles with a range of shapes, which are often referred to as 'stone-lines' when these form a significant horizontal layer within the intermediate nodular layer, are not well understood and have given rise to numerous questions. Various theories, mainly the allochthonous, the autochthonous, and the 'mixed' theory, have indeed been invoked to explain 'stone-line' emplacement. However, their implications are often inconsistent with field observations and their arguments do not therefore convincingly support an unique scenario.

To quantitatively examine the mechanisms involved in the development of lateritic structures and to characterize and quantify the processes leading to 'stone-lines' emplacement, a transcontinental study based on measurements of *in situ*-produced ^{10}Be and ^{26}Al concentrations in the lattice of a primary mineral, the quartz, has been initiated.

The studied African sites are located in different environmental settings. In the stable West African Craton in northern Burkina Faso, results from outcropping quartz veins suggest that the mean erosion rate in this region is about 3–8 $m.Myr^{-1}$. In addition, quartz cobbles, presently at depths of a few meters in a palaeochannel filled with rapidly deposited fluvial-colluvial material, have ^{10}Be distribution that suggest that the lowland lateritic surface may have formed during an erosive episode, presumably associated with a wetter climate, roughly 300 kyr BP. In Southwest Burkina Faso at Larafella, the exponential decrease in ^{10}Be concentration observed along a quartz vein from the lowland lateritic system corresponds to the decrease in its production rate associated with attenuation of cosmic rays, and thus indicates an autochthonous development. Models of the ^{10}Be depth profile in this unit suggest that this surface has been subject to erosion at a mean rate of ~2 $m.Myr^{-1}$ and that ~1.5% of the surface ^{10}Be production rate is associated with muon-induced reactions. In a contrasting environment (tropical rain forest (Malemba, Congo)), the ^{10}Be concentrations measured in quartz vein and in round and angular cobbles, when compared with data from Larafella, suggest that the angular cobbles have been transported a few meters from the quartz veins by downslope lateral transport, whereas the round cobbles have an allochthonous origin. Models of ^{10}Be distributions at this site yield an erosion rate of ~12 $m.Myr^{-1}$, and a rate of lateral displacement on the order of 60 $m.Myr^{-1}$. The extent of biopedoturbation in the upper soil layers has been clearly demonstrated through the measurements of ^{10}Be concentrations in material from several pits at the Goyoum hill (Cameroon) which develops under forest cover in permanently humid and percolating environments. In addition, the ^{10}Be concentrations measured in the saprolite of this site indicate the occurrence of burial during the development of the studied sequence. This is confirmed by examination of the $^{26}Al/^{10}Be$ ratio as a function of the ^{10}Be concentration measured in quartz cobbles from the 'stone-line' travelling through the nodular layer. Moreover, the combined used of both cosmogenic nuclides permits to calculate the 'stone-line' minimum burial time.

Three Brazilian lateritic systems were studied in order to characterize and quantify processes involve in their development. Two of these sites, a quartz vein at Gentio do Ouro, and a quartz vein and its connected 'stone-line' at Itaberaba, are located on the São-Francisco craton. The other, a 'stone-line' without obvious connection to any quartz vein at Cuiaba, is located on the edge of the Amazonian craton. Results from the bed rock embedded quartz vein that outcrops at Gentio do Ouro lead to a calculated mean erosion rate of 2.5 $m.Myr^{-1}$. At Itaberaba, the ^{10}Be content of the surficial sample yields a mean erosion rate of 9.0 ± 0.5 $m.Myr^{-1}$. In addition, the ^{10}Be concentration increase as a function of the distance from the quartz vein observed in the quartz samples from the connected 'stone-line' constrains a model of 'stone-line' emplacement and imply a rate of lateral displacement on the order of 70 $m.Myr^{-1}$. By contrast, the constant ^{10}Be concentration measured within the rounded quartz cobbles all along the Cuiaba 'stone-line' suggests that it most likely results from almost contemporaneous rapid events that occur at least 500 kyr ago. The proposed scenario involves sheet washing at the surface of the lateritic palaeolandscape leading to surficial dispersion of allochthonous quartz cobbles immediately followed by colluvial deposition of weathered lateritic material.

All these results demonstrate the potential of the use of *in situ*-produced cosmogenic nuclides for understanding the history of formation of laterites, the emplacement of 'stone-lines' and for differentiating between systems formed through in situ chemical weathering and mechanical transport.

References

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