INSTITUT DE FRANCE
Académie des sciences

EROSION ET ALTERATION : DES MECANISMES ELEMENTAIRES AUX CONSEQUENCES GEODYNAMIQUES

EROSION AND WEATHERING: FROM FUNDAMENTAL MECHANISMS TO GEODYNAMIC CONSEQUENCES

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« SYMPOSIUM EBELMEN »

COLLOQUE DE L'ACADÉMIE DES SCIENCES

26 -27 MARS 2012

A l'Institut de France
23, quai de Conti
75006 Paris

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Érosion et altération : des mécanismes élémentaires aux conséquences géodynamiques

Des progrès importants ont été réalisés au cours de ces vingt dernières années dans la compréhension et la modélisation des processus d'altération et d'érosion, que l'on cherche à caractériser leurs rôles respectifs dans les cycles géologiques et climatiques ou à comprendre leurs réponses aux forçages tectoniques, climatiques ou anthropiques.

L'Académie des Sciences organise, les 26 et 27 mars prochains, un colloque international dédié à ces travaux. Ce colloque intitulé : « Érosion et Altération: des mécanismes élémentaires aux conséquences géodynamiques », permettra d'illustrer les concepts, approches et méthodes qui ont été développés pour l'étude de ces questions. Il réunira les interventions de plus de 25 conférenciers invités qui présenteront les résultats des avancées les plus récentes dans leur discipline.

Le colloque s'articulera autour de cinq sessions thématiques : (i) Mécanismes de l'Altération; (ii) Altération chimique et érosion mécanique; (iii) Transport sédimentaire ; (iv) Érosion - climat - géodynamique; (v) Activité anthropique et érosion. Il retracera également des chapitres de l'histoire de notre compréhension des cycles géodynamiques externes, en particulier les travaux du scientifique français ***Jacques-Joseph Ebelmen*** (1814-1852), qui jetèrent les bases du cycle du carbone tel que nous le décrivons aujourd'hui.

Un fascicule thématique réunira l'ensemble des travaux présentés au colloque et sera publié dans la série Geoscience des Comptes Rendus de l'Académie des Sciences.

Le colloque est ouvert à la communauté scientifique dans son ensemble (enseignants et chercheurs des Etablissements publics et privés et, en particulier aux post-doctorants et doctorants), le but étant de favoriser le plus large débat possible. L'inscription pour assister au colloque se fera en ligne (colloques@academie-sciences.fr) ; elle est indispensable mais sans frais.

Les membres du comité d'organisation.

Erosion and weathering: from fundamental mechanisms to geodynamic consequences

Major strides have been made during the past twenty years toward a better understanding and modeling of the weathering and erosion processes, and aimed at both characterizing their respective role in the geological and climatic cycles, and understanding their responsiveness to tectonic, climatic and anthropic forcing.

The French Académie des Sciences convenes an international conference on March 26 and 27, 2012, in Paris, dedicated to the recent studies in this field. Entitled: «Erosion and Weathering: from fundamental mechanisms to geodynamic consequences», the conference will give an opportunity to illustrate the new concepts, approaches and methods developed to study these topics. More than 25 invited speakers will present the most recent results in their individual discipline.

The conference is centered around the five following thematic sessions : (i) Weathering processes ; (ii) Chemical weathering and erosion ; (iii) Sediment transport ; (iv) Erosion-climate-geodynamics; (v) Anthropogenic activity and erosion. The conference will also present a historical summary of our understanding of the external geodynamic cycles, and more particularly the work of ***Jacques-Joseph Ebelmen*** (1814-1852), the French scientist who threw the foundation of the carbon cycle as we know it today.

All of the conference presentations will be collected in a thematic brochure, which will be published in a special issue of the Geoscience series of the Comptes Rendus de l'Académie des Sciences.

The conference is open to all members of the scientific community, including teachers and researchers of public and private institutions and, more particularly, to PhD/Graduate and Post Graduate students; its purpose is to extend the debate and discussion as much as possible.

On line (colloques@academie-sciences.fr) registration is free but compulsory.

The members of the organizing committee

PROGRAMME

Lundi 26 mars 2012
Fondation Simone et Cino del Duca
10, rue Alfred de Vigny, 75008 Paris

9h15 - Ouverture du colloque et introduction / *Opening of the symposium*
Claude Allègre, Membre de l'Académie des Sciences, France

Mécanismes de l'altération / ***Weathering processes***

9h30 - Jacques-Joseph Ebelmen, 1814-1852, The Founder of Earth System Science
Robert A. Berner, Pr., Yale University, USA

9h55 - The discovery of the carbon cycles
Matthieu Galvez, Dr., IPGP, CNRS-INSU, Paris, France

10h20 - Towards consistent kinetic laws to describe chemical weathering
Jacques Schott, DR., GET, CNRS-INSU, Toulouse, France

10h45 - 11h25 : Coffee break

11h25 - Simple model of dynamical discharge-concentration relationships in rivers
Eric Lajeunesse, Phys.Adj., IPGP, CNRS-INSU, Paris, France

Erosion chimique – érosion mécanique / ***Chemical weathering and erosion***

11h50 - Global Erosion and Weathering : Where, when and how much ?
Friedlhelm Von Blanckenburg, Pr. , Deutsches GeoForschungsZentrum, Potsdam Germany

12h15 - Global control of carbonate weathering rates
*Jérôme Gaillardet***,** Pr., IPGP, CNRS-INSU, Paris, France

12h40 - 14h00 : Lunch

14h00 **– Landscape scale linkages in critical zone evolution**
Suzanne P. Anderson, Pr., University of Colorado, Boulder, USA

14h25 - Contribution of non-traditional stable isotopes (B,Ca,Li, Mg) to the quantification of soil-water-plant exchanges
Anne-Désirée Schmitt and al., MdC, CNRS-INEE, Univ. de France-Comté, Besançon, France

14h50 - Continental weathering and biological cycling : tracing with silicon isotopes
Sophie Opfergelt, Dr., UCL, Louvain-la-Neuve, Belgique

15h15 - 15h45 : Coffee break

Transport sédimentaire / ***Sediment transport***

15h45 - Sediment transfer in rivers : linking sediment grain motions with geomorphic dynamics with a focus on process stochasticity
Philippe Davy, DR., CNRS-INSU, Géosciences Rennes, France

16h10 - U-Th comminion ages and sediment transport times
Donald J. De Paolo, Pr., Lawrence Berkeley National Laboratory, USA

16h40 - Riverine particulate material dissolution in seawater and its implication for the global cycles of the elements
Erik Oelkers, DR., GET, CNRS-INSU,Toulouse, France

Mardi 27 mars 2012

Institut de France / Académie des sciences

Grande Salle des Séances

23 quai Conti, Paris 6ème

9h00 - Sediment transfer and the hydrological cycle of Himalayan rivers in Nepal
Stéphane Bonnet, Pr., GET, CNRS-INSU, OMP, Université de Toulouse, France

9h25 - Geochemical heterogeneity of sediment load in the Brahmaputra and Ganga rivers
Christian France-Lanord, DR., CRPG, CNRS-INSU, Nancy, France

9h50 - U-series nuclides in the Ganga sediments – insight into the sediment transfer time
François Chabaux, Pr., LHyGeS, CNRS-INSU, Université de Strasbourg, France

10h15 - Contribution of soil erosion to sediment export of the French rivers
Olivier Cerdan, BRGM, Orléans, France

10h40 - 11h15 : Coffee break

Erosion – climat – géodynamique / ***Erosion – climate – geodynamics***

11h15 - Interaction of Himalayan climate with erosion rates and processes in central Nepal
Doug Burbank, Pr., University of California, Santa Barbara, USA

11h40 - Plateau Building and Erosion : the role of large rivers in the evolution of relief in active orogens
Jérôme Van der Woerd, CR., IPGS, CNRS-INSU, Université de Strasbourg, France

12h05 - Impact of late-Cainozoic climate change on relief development and orogen dynamics
Peter Van der Beek, Pr., Université Joseph Fourier, Grenoble, France

12h30 - 14h00 : Lunch

14h00 - Dynamic vegetation modelling and its importance to study weathering processes and related climate feedbacks
Louis François, Dr., Université de Liège, Belgique

14h25 - Climate change and the future of continental weathering

Yves Godderis, DR., GET, CNRS-INSU, Toulouse, France

14h50 - Biogeochemistry of major and trace elements in watersheds of the Arctic Ocean basin : the change of fluxes, sources and mechanisms under the climate warming prospective
Oleg Pokrovsky, DR., GET, CNRS-INSU, Toulouse, France

15h15 -15h45 : Coffee break

Activité anthropique et érosion / ***Anthropogenic activity and erosion***

15h45 - Sustaining Soil at the Heart of Earth's Critical Zone
Steve Banwart, Pr., University of Sheffield, UK

16h15 - Impact of agriculture of the chemical weathering of silicates
Catherine Keller, Pr., CEREGE, Université Paul Cézanne, Aix-Marseille, France

16h40 - Evidence of short-term clay evolution in soils under human impact
Sophie Cornu, DR., INRA, Aix-Marseille, France

17h05 : Clôture / *Conclusion*

ABSTRACTS

MÉCANISMES DE L'ALTÉRATION

WEATHERING PROCESSES

Jacques-Joseph Ebelmen, The Founder of Earth System Science

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The fundamental principles of the factors affecting the global carbon cycle, the global sulfur cycle and the levels of atmospheric CO_2 and O_2 over long term (multimillion year) time scales were first elucidated by Jacques-Joseph Ebelmen in 1845. He covered all major processes in such a correct manner that no appreciable changes have been elucidated since then. Unfortunately, his ideas were forgotten and were independently deduced by others only 100 to 150 years later. In this paper his reasoning is shown in detail, via a number of original quotations, and the results of a mathematical model by the author for CO_2 and O_2 over the Phanerozoic Eon (past 542 million years) is presented. In agreement with Ebelmen's predictions, there apparently have been large changes in the levels of atmospheric CO_2 and O_2 over geologic time.

The discovery of the carbon cycles

Matthieu GALVEZ[1] and Jérôme GAILLARDET[2]

[1]*Equipe de géochimie des isotopes stables, Institut de Physique du Globe de Paris*
[2]*Equipe de géochimie-cosmochimie, Institut de Physique du Globe de Paris*

The concept of carbon cycle (« rotation ») was discovered at the end of the 18th century and finds its root in the revolutionary methodological breakthrough introduced by Antoine Laurent Lavoisier in 1789. The invention of mass equilibrated chemical reactions allowed scientists from different disciplines to show that the growth of plant and the action of water on rocks are mechanisms that consume atmospheric « carbonic acid » (CO_2). Simple mass budgets quickly led to the conclusion that compensating mechanisms should exist in order to maintain the atmospheric composition. Despite the fact that carbonic acid was already known to be fixed in limestone (« fixed air ») and the fact that the role of carbonic acid on rock weathering had been proposed before its 1845 paper, Ébelmen was really the first to envisage the « rotation » of carbon at different timescales between compartments of the Earth and to establish the analogy between the biological short term cycle of carbon and the long term geological cycle. We will review the different works that led plant physiologists, geologists and chemists to the discovery of the carbon cycles and the role played by Ébelmen.

Towards consistent kinetic laws to describe chemical weathering

Jacques SCHOTT, Erik H. OELKERS, Oleg S. POKROVSKY, Yves GODDÉRIS

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Knowledge of the mechanisms and rates of mineral dissolution and precipitation, especially at close to equilibrium conditions, is essential for describing the temporal and spatial evolution of natural processes like weathering and its impact on CO_2 budget and climate. The Surface Complexation approach (SC) combined with Transition State Theory (TST) provides an efficient framework for describing mineral dissolution over wide ranges of solution composition, chemical affinity, and temperature. There has been a large debate for several years, however, about the comparative merits of SC/TS versus classical growth theories for describing mineral dissolution and precipitation at near to equilibrium conditions. The paucity of combined microscopic and macroscopic rate measurements on identical samples has prevented reconciliation of the surface coordination chemistry and crystal growth approaches.

This study considers recent results obtained in our laboratory on oxides, hydroxides, silicates and carbonate minerals dissolution and precipitation at near to equilibrium conditions via the combination of complementary techniques including batch and mixed flow reactors, hydrogen-electrode concentration cell (HECC), potentiometric titration cell, and hydrothermal atomic force microscopy (HAFM). Results show that the dissolution and precipitation of hydroxides, kaolinite and hydromagnesite powders of relatively high surface area closely follow SC/TST rate laws with a linear dependence of both dissolution and precipitation rates on fluid saturation state even at close to equilibrium ($\Delta G < 500$ J/mol) conditions. This occurs because sufficient reactive sites are available for dissolution and growth (kink, steps, edges) allowing reactions to proceed via the direct and reversible detachment/attachment of reactants at the surface. In contrast, for quartz, calcite and magnesite crystals, whose surfaces contain much fewer active sites, crystal growth (and dissolution) rates at near equilibrium conditions exhibit either a parabolic (defect assisted nucleation, spiral growth) or linear (attachment/detachment at reactive sites) dependence on saturation state depending on the treatment of the crystals before the reaction. For example, after extended dissolution (a process that creates active sites) both quartz and magnesite crystals exhibit transient linear growth rates. SC/TST rate laws can thus be applied only to those minerals that have abundant reactive sites density. It follows that determination of the active site density and origin (screw dislocations, preexisting steps…) on mineral surfaces is critical to identifying the mechanism and thus the rate equations that can describe quantitatively mineral dissolution and precipitation rates as a function of fluid composition in natural processes. The consequences of these results for describing past weathering events or predicting the future impact of climate change on weathering rates and related export fluxes and CO_2 consumption are illustrated.

Simple model of dynamical discharge-concentration relationships in rivers

Eric LAJEUNESSE [1], DEVAUCHELLE O.[1], METIVIER F.[1], DESERT C.[1], CRISPI O.[1], GAILLARDET J.[1], DIDON-LESCOT JF[2], LIU YOUCUN[3], YE BAISHENG [4]

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[4]*The States Key laboratory of China, Cryospheric Science, Cold and Arid Region Environmental and Engineering and Research Institute, Chinese Academy of Sciences, 260 Donggang West road, Lanzhou, China*

The concentration of solutes in rivers typically decreases as water discharge increases, although more slowly than simple dilution would account for. Most theories describing this phenomenon are based either on multiple reservoirs dynamics, or on the distribution of travel times associated with distinct flow paths (such as runoff and groundwater flow). We focus here on the dissolution dynamics in a single aquifer with a free-surface. To do so, we couple classical groundwater-flow equations to a first order dissolution mechanism. In this framework, rainfall dilution is moderated by an increase of dissolution, the intensity of both effects varying along the aquifer. In permanent regime (i.e. for a slowly varying rainfall rate), the aquifer boundary conditions control the continuous transition between two asymptotic regimes. If the aquifer extends far below the stream level, the theoretical discharge-concentration relation corresponds to the ``working model" proposed by Johnson in 1969, thus providing a physical interpretation of its parameters. Conversely, if the stream level is close to an impervious layer, the concentration in the river decreases with discharge more slowly than in the deep aquifer regime. We show that field data, provided they extend over a sufficient range of discharges, allow us to distinguish between the two regimes. Finally, we present preliminary results about dissolution dynamics during flood events.

ÉROSION CHIMIQUE-ÉROSION MÉCANIQUE

CHEMICAL WEATHERING AND EROSION

GLOBAL EROSION AND WEATHERING: WHERE, WHEN, AND HOW MUCH ?

Friedhelm VON BLANCKENBURG*[1], Jean L. DIXON[1], Jane WILLENBRING[2]

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Common gospel holds that the rise of mountains in the late Cenozoic has increased global rates of silicate weathering, and, as a consequence, increased withdrawal of atmospheric CO_2. Seawater isotope ratio curves of radiogenic Sr, radiogenic Os, and most recently, stable Li [1] supposedly testify to this change. We challenge this hypothesis on three grounds.

1) A compilation of weathering and denudation rates at both the soil scale and the river catchment scale show that "speed limits" restrict both soil formation (270 t km^2 yr^{-1}, or 0.1mm yr^{-1}) and silicate weathering (135 t km^2 yr^{-1}). Even in high, active mountains, these limits are obeyed. We use a global topographic model to show that due to the combination of weathering speed limit and the small spatial extent of active mountain belts, areas in which erosion exceeds the soil formation speed limit contribute <10% to global weathering fluxes today. In the geologic past, due to the limited range of weathering rates imposed by speed limit, large global changes in uplift and erosion would have resulted in only small changes in global weathering.

2) A reassessment of global and regional erosion rates inferred from global sedimentation rates has shown that a supposed increase in global mountain erosion rates in the late Cenozoic is only an apparent one, and that the underlying increase in sedimentation rates is due to incomplete preservation of sedimentary strata [2].

3) An increasing body of evidence shows that the seawater curves of radiogenic Sr and Os isotope ratios record provenance of these elements [3], or the increasingly glacial contribution to erosion [4] rather than weathering rates. The new stable Li isotope data [1] is intriguing, but we still lack detailed insight into these metal stable isotope systems to attribute their variability with certainty to an increase in terrigenous weathering. In contrast, the ocean

^{10}Be(meteoric)/^{9}Be ratio, a weathering proxy that combines an isotope of constant flux with a stable one of weathering-dependent flux, is steady over the last 10My [2]. It is therefore unlikely that changes in CO_2 withdrawal over this period were engineered by silicate weathering.

We conclude that the optimal conditions for CO_2 withdrawal are those where a large fraction of the terrestrial Earth surface is soil covered, and is eroding near soil production speed limit. At lower global denudation rate, global soils will be transport-limited. The consequence of such a low global denudation regime is that the potential for feedbacks between climate, weathering, and CO_2 withdrawal to operate is low. In such a period the Earth system could fail all climate weathering feedbacks.

[1] Misra and Froelich (2012) *Science* in press
[2] Willenbring and von Blanckenburg (2010) *Nature* 465
[3] Kashiwagi et al. (2008), *Palaeogeog Palaeocl Paleoecol* 270
[4] Clark et al. (2006) *Quat Sc. Rev*. 25

The global control of carbonate weathering rates

Jérôme GAILLARDET[1,] Damien CALMELS[1] and Louis FRANÇOIS[2]

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[2]*Université de Liège, Belgium*

There is a consensus in the geochemical literature of the global carbon cycle that carbonate weathering is not important in the regulation of the atmospheric content of the atmosphere. This view is oversimplified for several reasons, the first of which being that on relatively short time scales, and transiently, carbonate weathering should matter. Given the modern flux of carbonate weathering deduced from the inversion of river geochemistry (0.3 GtC/yr), it is critical to understand more about the controlling factors that affect the weathering rate of carbonates. It appears more and more clearly that any future climatic scenarios should take into account the interaction between carbonate and atmospheric-soil CO_2.

In this paper, we have compiled the available data on carbonate weathering rates from the literature and from data from the Provence area. We show that weathering rates of carbonate (and associated CO_2 consumption) respond to temperature in a non linear way, the highest weathering rates being found in the temperate zone. Lowest weathering rates are found in the arctic and equatorial regions. This relationship with climate is not that expected using a thermodynamic approach assuming equilibrium between atmospheric CO_2 and carbonate rocks, indicating other first order factors control the chemical weathering of carbonates.

We propose that soil CO_2, generated by autotrophic and heterotrophic activity is a dominant controlling factor. In support to this explanation, the ecological model published by Calmels et al. 2012 is used and applied to a climatic gradient in the temperate zone. This model does confirm the high sensitivity of carbonate weathering to vegetation type, temperature, but also to soil properties such as soil porosity and soil hydrology.

This study shows that carbonate weathering responds to climate forcing through the response of vegetation and ecosystems and outlines the need to understand more about the links between soil respiration and dissolved carbonic acid formation.

Landscape scale linkages in critical zone evolution

Suzanne PRESTRUD ANDERSON[1*], Robert S. ANDERSON[2], and Gregory E. TUCKER[3]

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The character of the weathered zone at the Earth's surface, known as the critical zone, reflects the integrated effects of weathering and erosion over time. At the base of the critical zone, weathering processes advance an interaction front where fresh rock is altered under the influence of atmosphere, meteoric water, and living organisms. Within the critical zone, weathering processes continually modify material, generating saprolite and soils. Erosion processes mobilize rock into soils and remove mass from the system; losses are highest at the land surface. This one-dimensional view of critical zone evolution can explain how a particular profile evolves over time [1]. The problem of critical zone evolution is much richer, however, if we consider landscape scale teleconnections that link the evolution of profiles in different regions.

We use the Boulder Creek Critical Zone Observatory to illustrate landscape-scale linkages that drive critical zone evolution through feedbacks that work both upstream and downstream. We focus on two styles of teleconnection: 1) down-gradient transfer of sediment and water, and 2) changes in river baselevel that travel upstream as propagating waves of incision. These particular connections feature strongly in the evolution of Boulder Creek. Other regions will respond to different drivers; the essential point is that regions are linked by transfers of mass and by boundary conditions set by external processes.

Downstream mass transfers

Important topographic features of the Boulder Creek watershed can be attributed to variations in sediment flux from the headwaters. The broadest topographic features are set by tectonic history; climatically modulated sediment flux and its feedbacks are responsible for sculpting the landscape on this template. Boulder Creek flows east from crest of the Colorado Front Range to the western edge of the High Plains, spanning elevations from ~4000 m to ~1500 m. A dramatic transition from high elevations and high relief to low elevations and low relief corresponds to the lithologic boundary between crystalline rocks of the Front Range, which were displaced by uplift in the Tertiary Laramide orogeny into juxtaposition with Cretaceous seaway sediments of the High Plains. During the Pleistocene, the range crest supported glaciers while the surrounding alpine and subalpine landscape experienced periglacial conditions. High erosion and sediment fluxes from these areas during glacials cloaked downstream channels in alluvium, and arrested channel incision on the Plains. Conversely, low erosion and sediment fluxes during interglacials promoted incision of easily eroded Cretaceous sediments on the High Plains, stranding broad alluvial terraces on the Plains [2]. The toe of the glaciated and periglacial area marks a fulcrum point between the locus of erosion versus non-erosion or deposition. The balance shifted between eroding headwaters/depositional lowlands during times of glacial climate to non-eroding headwaters/eroding lowlands during interglacials. The shift between these states was a response to variations in sediment flux from the headwaters, which are themselves controlled by critical zone processes of bedrock weathering and hillslope sediment transport. Thus, downstream landscapes flip between states of erosion and deposition depending on the rates of critical zone processes in upstream landscapes.

Upstream propagating base-level lowering

Since the late Cenozoic, exhumation of the Plains has outpaced the erosion of the crystalline rock of the Front Range, giving rise to the abrupt mountain front at the edge of the plains. This imbalance also establishes a steep channel gradient that promotes propagation of a fluvial knickzone upstream into the crystalline headwaters. For ~10 km between the mountain front and the present position of this knickzone, Boulder Creek (like other east-flowing rivers in the Front Range) is confined to a narrow canyon with steep walls. The upstream-propagating knickzone lowers the baselevel for the slopes and tributary catchments that flank the canyon. This baselevel change in turn incites a cascade of responses, ranging from lowering the watertable to stripping of mobile regolith from slopes.

These examples show where critical zone processes and erosion excite a two-way response between upstream and downstream parts of a landscape. Events in one area affect other areas through the connections of sediment, water, and boundary conditions.

[1] Anderson et al. (2007) *Elements* **3**, 315-319. [2] Dühnforth et al. (2012) *JGR-Earth Surface* (in press)

Contribution of non-traditional stable isotopes (B, Ca, Li, Mg) to the quantification of soil-water-plant exchanges

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The alteration of silicate minerals of the continental crust plays a key role in the (bio)geochemical cycles of elements, and in the carbon cycle. However, several major uncertainties remain unresolved, that preclude precise quantification of its present-day and past impact on the oceanic budget and on climate variations. In particular, the role of plants, for example during rapid changes of the continental biomass and of vegetation species, on the chemical alteration intensity of silicate minerals is poorly constrained yet. Soil mineralogy and chemistry evolve by contact with weathering agents supplied mainly by living organisms (plants and microorganisms). The corresponding mechanisms of soil-water-plant interactions, as well as the geochemical fluxes and exchanges linking these compartments are nevertheless difficult to be determined with classical geochemical tools.

Analytical improvements from the last decade have allowed the geochemical community to develop precise measurements of new isotopic systems. Among these “non-traditional” or "novel" stable isotopic systems, B, Ca, Li and Mg have been studied at the soil-water-plant interface. Ca and Mg are two major elements, essential nutrients for plants and sensitive to acidification of soils developed on base-poor bedrocks. They are also intimately linked to the long-term carbon cycle. B and Li are mainly concentrated in silicate rocks and their isotopic systems present the advantage to be highly fractionated during water-rock interactions, including soil-forming reactions. Unlike Li, but similar to Ca and Mg, the B geochemical cycle is also controlled by the vegetation cycling.

Consequently, B, Ca, Li and Mg isotopic systems provide a great opportunity to quantify the intensity and the environmental conditions in which these reactions occur - or have occurred in the past. The study of these isotopic systems in monolithological watersheds of variable size has revealed variable amplitudes of isotope fractionations (from 1.25‰/a.m.u. for Ca up to 40‰ for Li). A common feature to these four non-traditional isotopic systems is that isotope signatures of natural waters do not directly reflect the signature of the bedrock, but rather the dynamic of dissolution/precipitation reactions or interactions with vegetation. However, these investigations are limited since, in near-surface environments, the identification of the fractionation mechanisms is not easy to characterize. Indeed, various effects (e.g. adsorption, ion-exchange, secondary precipitations, biological uptake and recycling) can overlap or counterbalance each other. The identifications of the fractionating processes have thus been performed, in parallel, through experimentations under controlled conditions. These experimental investigations allow the determination of the key controlling parameters and of the control laws that could ultimately be applied to natural records.

Continental weathering and biological cycling: tracing with silicon isotopes

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On geological time-scales, the chemical weathering of continental silicate rocks modulates global climate by consuming atmospheric CO_2. In the critical zone (CZ), silicon (Si) incorporation into secondary minerals, or biological Si uptake fractionates Si isotopes, thereby providing an opportunity for disentangling the biotic and abiotic contributions to chemical Si fluxes exported to rivers. In this review, we first outline Si isotope variability at the Earth's surface and then provide a detailed discussion on the processes controlling Si isotope fractionations in the CZ. Specifically, we address three questions: (i) Do Si isotopes reflect weathering degree in the CZ?, (ii) What are the limitations of Si isotopes for quantifying biological Si recycling in the CZ?, (iii) How do weathering processes in the CZ impact riverine Si isotope compositions, and can we use Si isotopes in rivers as a proxy for continental silicate weathering ? Some research perspectives are also proposed.

TRANSPORT SÉDIMENTAIRE

SEDIMENT TRANSPORT

Sediment transfer in rivers: linking sediment grain motions with geomorphic dynamics with a focus on process stochasticity

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Sediment grain dynamics (erosion, transport, deposition) is *the* key process controlling the morphodynamics of rivers (alluvial or bedrock), and the associated chemical transport along the drainage network. Despite the large gap between grain and landscape scales, most of the upscaled erosion equations are justified by, and consistent with, processes that operate at the grain scale. Einstein H. [1947] was one of the first to link the movements of grains, with successive resting periods and motions, and the resulting sediment fluxes. He showed that the bedload flux is proportional to the ratio of the grains step (transport) length to the average resting period.

In this paper, we review the concepts that have been developed to link grain motion and sediment flux equations since Einstein's pioneering work. We address the form and nature of erosion/transport equations but also the way these processes can be quantified in the field. We show that fluvial processes at various scales depend on two terms: the sediment transport length, and the bed erosion rate. The sediment transport length plays a critical role in controlling the partitioning between bedload and suspended load, the transport capacity of rivers, and even the instabilities of fluvial regimes. We show in particular how the formation of sediment bars, which in turn controls the braiding instability, can be related to the sediment transport length. We also emphasize the critical role of the volume of immobile sediment grains, and the way sediments are trapped into through various processes (e.g. river aggradation/erosion, bar or channel mobility). This trapping effect results in a distribution of grain resting time that largely fixes both the average velocity of particles and their dispersion.

The issue of process stochasticity, which is essential for assessing long-term fluvial dynamics, has rarely been addressed. The distribution of the long-term parameters (either the transport length or the sediment layer volume) and their long-term averages require to take into account the time and spatial variability of erosion/transport events. We discuss both the *intrinsic* variability – i.e. observed for stationary flow conditions –, and the *extrinsic* variability of flow discharges and stochastic sediment supply (e.g. landslides). Intrinsic variability emerges through deterministic variables such as grain size variability, or purely hydrodynamics aspects related to flow turbulence. The emergence of bedforms during bedload transport and larger scale fluvial instabilities (such as braiding) is another source of internal system variability whose contribution over the long-term is still difficult to assess. Extrinsic variability resulting from high-frequency fluctuations in river flow and hillslope sediment supply has been shown to play a dominant role in the long-term dynamics of mountain river incision. For alluvial rivers, this effect has not been studied yet. Considering the very broad distribution of flow discharges, whether or not the long-term average of fluvial processes in alluvial rivers is controlled by the rare extreme events or by the large number of intermediate ones is an issue that the simplified formalism described above can help to solve.

U-Th comminion ages and sediment transport times

Donald J. DE PAOLO, Lawrence Berkeley National Laboratory, USA

No abstract received

Riverine particulate material dissolution in seawater and its implication for the global cycles of the elements

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A survey of the chemistry of global rivers reveals that the total mass of material transported to the oceans as particulate material exceeds by a factor of roughly 25 that transported to the oceans in dissolved form. The relative significance of particulate transport depends strongly on the element; the ratio of particulate to dissolved transport is no more than ~3 for soluble elements such as Ca, Mg, and Sr, but in excess of 200 for insoluble elements such as Al, Fe and Nd. The degree to which particulate transport impacts ocean chemistry and global elemental cycles depends critically on the reactivity of riverine transported particulate material in seawater.

The reactivity of particulate material is seawater is difficult to assess directly because the fluid is saturated or supersaturated with respect to most element in the periodic table. As such element release from particulate material is closely matched by precipitation of secondary phases. This challenge is overcome in this study by monitoring the isotopic evolution of selected elements in seawater during its reaction with a variety of particulate material samples collected from rivers throughout the world.

We have focused our research to date on the behavior of Sr and Nd, representative of the most and least soluble elements transported to the oceans. Batch experiments demonstrate that between 0.15 and 27.36 % of Sr is liberated from riverine particulates to seawater within 6 months. The rates of release are dependent on surface area and particulate composition, with volcanic riverine material more reactive than continental riverine particulates. Corresponding batch experiments demonstrate that sufficient Nd is released to reset the Nd isotopic

composition of sweater in a week or less. The observed rapid elemental release rate from riverine particulate material has important consequences for both chemical and isotopic mass balances in the ocean and the application of the isotopic weathering proxies to the geological record. The dissolution of riverine particulate material is likely to at least partially account for the currently debated imbalance between Sr sources to the oceans.

Sediment transfer and the hydrological cycle of Himalayan rivers in Nepal

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In the Himalayas, the well-defined monsoon seasonality (Indian Summer Monsson), coupled to active tectonics and strong relief provides an ideal environment to investigate the transfer of sediment in rivers, linked to the hydrological cycle. For this purpose, we present here the analysis of ~30 years of daily precipitation and discharge within major catchments in Nepal as well as daily suspended sediment data for 13 gauging stations. In all the studied catchments, **w**e observe an annual anticlockwise hysteresis loops between precipitation and discharge, in both glaciated and unglaciated catchments and independently of the lithological nature of their bedrock. Anticlockwise hysteresis loops imply that precipitation is temporarily stored within the catchments and not transferred directly to the river during pre-ISM and ISM seasons, whereas the storage compartment is drained during post-ISM. We show that the main mechanism explaining the hysteresis effect is a transient storage of water in a groundwater unit and we show that this aquifer is predominantly fractured basement. The estimated aquifer storage capacity is ~180 mm, representing ~28 km^3 for the three main catchments of Nepal. Modelling also indicates that the annual volume of water flowing through this groundwater system represents ~2/3 of the annual river discharge, approximately 6 times higher than the contribution of glacial and snow melt to river discharge.

In all the Himalayan Rivers in Nepal, suspended sediment concentrations vary through the seasons, displaying an annual clockwise hysteresis effect when compared to river discharge. We observe that these hysteresis loops disappear when suspended sediment fluxes are directly compared to the direct discharge, that is to the total discharge minored form low-frequency baseflow variations due to groundwater. We consequently demonstrate that these annual clockwise hysteresis loops result from a dilution effect by groundwater during post-ISM season rather than from a supply effect as considered usually. We infer a rating model to calculate erosion rates directly from long river discharge chronicles. We show that normalized sediment fluxes follow the same trend with normalized storm discharge, which implies that all rivers basins show the same erosion behavior, independently from their location, size and catchment characteristics. Finally, erosion rates calculated from suspended sediment fluxes range between 0.1 and 5.9 mm/yr.

We propose that material transport in Himalayan Rivers in Nepal depends on the supply of material from hillslopes, which is controlled by the occurrence of rainfall producing direct runoff. In other words, the rivers in the Nepal Himalayas are supply-limited and the hillslopes as contributing sources are transport-limited. Our data also suggest that erosion processes are not as much controlled by infrequently occurring extreme events, than by moderate ones with a high recurrence interval.

Geochemical heterogeneity of sediment load in the Brahmaputra and Ganga rivers

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River sediments act as integrators of erosion processes and their chemical and mineralogical composition can be used to trace both the origin of sediments and the intensity of weathering processes. Assessing the controlling factor of their chemical composition is important for the use of detrital sediments as paleo-erosion and paleo-weathering archives. At first order, the composition is controlled by hydrodynamic particle sorting effects. These can however be taken into account by sampling sediments throughout the whole water column (e.g. Lupker et al 2011, Bouchez et al. 2011). Temporally, in continental scale rivers, the composition of sediment load tends to be stable due to the buffer that large floodplain exert. The efficiency of this buffer depends, however, on the scale of the floodplain, on the residence time of the sediments in the river system and on the intensity of exchanges between the river and the floodplain.

Here we present geochemical data acquired on the Brahmaputra and Ganga rivers at their outflow in Bangladesh. Sampling has been performed during twelve monsoon campaigns from 2004 to 2010 and includes depth profile sampling of suspended sediments. Due to grain size and mineralogical hydrodynamic sorting that depends on instantaneous hydrodynamic conditions, the elemental ratios like the Al/Si ratio of the sediment can strongly vary between each campaign. Once this sorting effect is corrected, more subtle, but still significant, temporal variations are observed affecting both major and trace elements concentrations and Sr and Nd isotopic compositions

Brahmaputra displays the most striking variability. It can be detected on elemental concentrations such as Sr or on Sr and Nd isotopic compositions. Both are well correlated and derive from variable proportions of geological formations eroded in the basin. The end members are identified by analyses of the different tributaries of the Brahmaputra. Rivers draining the Himalaya sensu stricto have low [Sr] and ε_{Nd} comparable to those of the Ganga that is mostly Himalayan. In contrast, the Tsangpo-Siang river which drains the Transhimalaya and the southern edge of the Tibetan plateau is characterized by higher [Sr] and ε_{Nd}. Seven out of twelve sampling campaigns have stable compositions throughout the water column and are dominated by the Transhimalayan contribution, which confirms the extreme erosion of the Eastern syntaxes of the Himalaya. For five campaigns the shallow suspended load samples show more Himalayan compositions whereas the bottom and bed sediment have Transhimalayan compositions similar to those of other campaigns. This variability likely derives from heterogeneities of precipitation distribution over the basin that trigger contrasted discharge and sediment fluxes of the tributaries. It reveals that the sediment exchange between the Brahmaputra and its floodplain is relatively limited, which prevents an efficient buffering as observed for the coarser sand fraction from the bottom sediments. Comparable variability can be observed on the Ganga showing changes in source distribution between Himalayan and Southern tributaries of the Ganga. In both case, bed-sediment present stable compositions whereas variability affects primarily upper suspended load. It confirms that both types of sediments have different residence time in the system (Granet et al., 2010), underlines the complexity of sediment mixing during river transport and directly impacts the link between weathering and granulometry in floodplain.

Bouchez et al. (2011), G3 12: Q03008
Granet et al. (2010), GCA 74: 2851–2865
Lupker et al. (2011), JGR-ES 116: F04012

U-series nuclides in the Ganga sediments – insight into the sediment transfer time

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U-series disequilibria have the potential to bring information on the transfer time of sediments in alluvial plains, as recently illustrated in the study of U-Th disequilibria in sediments collected along the Ganga River and along one of its main Himalayan tributaries: the Narayani-Gandak river (Granet et al., 2007; 2010). Results suggest that U-series disequilibria in Ganges river sediments vary with grain size and sampling location. The range of observed U-series disequilibria can be explained by two-component mixing between a coarse-grained sediment end-member, represented by bedload and bank sediments, and a fine-grained end-member. Both end-members originate from the Himalaya but they underwent different weathering and transfer histories from the Himalaya to the plain. The coarse-grained sediment end-member transits slowly (i.e. > several 100's ky) in the plain whereas the fine-grained sediment end-member is transferred much faster (<a few ky or less), as indicated by the absence of significant variations in Th isotope composition of the fine-grained sediment end-members. Such an interpretation relies on the use of a realistic modeling of the relative mobility of U –series nuclides in the sediments during their transfer within the plain. It also assumes a negligible contribution of new and fresh sediments coming from the erosion of the plain substratum during the sedimentary transfer.

In order to test these preliminary results and interpretations on the Ganges Basin river system, sediments of the main Himalayan tributaries of the Ganges were sampled at the exit of the Himalayan range and at the outlet of their watershed just before their confluence with the Ganges. In each of the sampling (locations) sites, both bank or bedload sediments and suspended sedimentary load, from different depths of the water column, were sampled. These new data along with previously published data (Granet et al., 2007 ; 2010) point to a wide range of variation in Th activity ratios in bedload and suspended sediments at the scale of the Himalyan range. Such differences probably indicate that the sediments originate from different (geographical, geological, lithological, pedological..) units depending on the E-W position of the Ganga tributaries within the Himalaya range. Most important, the data indicate that bedload and suspended load exhibit, systematically, very different covariations of U and Th isotope ratios from upstream to downstream. These different trends of variations confirm the occurrence of different transfer histories within the plain for the coarse-grained and fine-grained sediments. They are a priori consistent with the long transfer time of the bedload sediments from the Himalayan range to the confluence with the Ganges, and with much shorter transfer time for the suspended sediments. Variations in the U-Th isotope ratios of suspended sediments recorded for the same sampling (location) site but at different seasons suggest that their transfer time could be as fast as a few months. These new data thus confirm the above intrepretation concerning the transfer times of sediments in the Ganges river system.

Granet M., Chabaux F., France-Lanord C., Stille P., Pelt E. (2007) Time-scales of sedimentary transfer and weathering processes from U-series nuclides: Clues from the Himalayan rivers, *Earth and Planetary Science Letters, 261, 389-406*.

Granet M., Chabaux F., Stille P., Dosseto A., France-Lanord C., Blaes E. (2010) U-series disequilibria in suspended river sediments and implication for sediment transfer time in alluvial plains : the case of the Himalayan rivers *Geochim. Cosmochim. Acta, 74, 2851-2865*

Contribution of soil erosion to sediment export of the French rivers

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Soil erosion is one of the major drivers of landscape evolution in Western Europe. However, depending on the geological and topographical settings, the miscellaneous forms of erosion may lead to very diversified morphological evolution. A key element is the link between the hillslope and the river. In this context, the objective of this study is to investigate to what extent eroded soil particles contribute to river sediment exports for the French major basins. The hillslope erosion rates are deduced from a distributed pan-European assessment of hillslope, rill, and interrill erosion by water, which was quantified interpolating erosion plot data as a function of topographical, land use, and pedological parameters. Sediment fluxes were mainly assessed from the French river quality database, using an improved rating curve approach from daily discharge data (IRCA), which allows the estimation of mean annual sediment load. The resulting mean annual suspended sediment loads show that French rivers export ca. 50 Mt of sediments per year to the seas among which ca. 17 Mt as particulate matter corresponding to a specific sediment yield of ca. 0.4 ton/ha/yr. Based on the soil erosion map, the estimated average gross erosion rate for the four largest French basins is ca. 1.4 t/ha/yr (which is comparable to the mean value for Europe). The largest basins (Loire, Rhône, Garonne and Seine) export the majority, but, no relation was highlighted between the mass of exported sediment and the size of the drainage basins. Moreover, large differences were observed between the different basins. For the Seine river basin and the Rhône river basin, erosion rates are comparable, with ca. 1.14 t/ha/yr for the Rhone, and ca. 1.80 t/ha/yr for the Seine; but the Rhône exports ca. ten times more than the Seine River. The ratio of gross erosion on sediment exports calculated here ranges from 6.8% for the Seine to more than 100% for the Rhône. We propose to use indices that represent the landscape patchiness and connectivity to explain these variations. A first application of this approach permits to draw different basin typologies.

ÉROSION –CLIMAT – GÉODYNAMIQUE

EROSION – CLIMATE - GEODYNAMICS

Interaction of Himalayan climate with erosion rates and processes in central Nepal

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The Indian monsoon delivers about 80% of the annual precipitation to the Nepalese Himalaya between June and September. Topography on the windward (southern) flank of the range modulates spatial variations in precipitation distribution along the length of the range. Where topography is stepped with an initial abrupt rise where the Himalaya abut the foreland and a second rise where topography ascends toward the high peaks, two bands of high precipitation prevail, each where relief passes a threshold value. A more uniform, northward rising topography localizes a single high-rainfall band near the front of the range. A dense meteorological network that was operated in the Marsyandi catchment from 1999 to 2004 gives more insight on spatial variability in precipitation. A ten-fold decrease in annual precipitation prevails between the rainfall peak (of ~4 m/yr) on the southern flank of the Himalaya and the semi-arid rain shadow 40-50 km to the north. Modest contrasts between ridge versus valley rainfall during the monsoon are replaced by strong altitudinally dependent precipitation contrasts in the winter. Above 4 km altitude, ~40% of the total precipitation arrives as winter snowfall. Four years of daily discharge measurements of water and suspended sediment on the main stem and several tributaries of the Marsyandi during the monsoon document a strong north-south gradient in average erosion rates. Based on a suspended-to-bedload ratio of 2:1 (as estimated from grain-sizes in a landslide-dammed lake), erosion rates range from ~0.1 mm/yr in the northern rain shadow to ~2 mm/yr in the monsoon-drenched south. This strong modern spatial gradient in erosion rates mimics the precipitation gradient across the same area and broadly scales with specific discharge. In the wetter regions, nearly a meter of monsoon rain is required before significant sediment fluxes due to landsliding occur. After this precursory meter, the daily rainfall required to trigger sediment pulses gradually decreases during the remaining monsoon season from ~4 cm to 1 cm. In the higher altitude rain shadow to the north, water discharge is more closely linked to temperature than to precipitation: a linkage suggesting that melting of snow and ice, rather than rainfall, modulates the runoff. The sediment flux in the rain shadow during the monsoon season displays a marked temporal hysteresis: fluxes broadly scale with discharge during the first two months of the monsoon, but decouple from discharge later in the monsoon. This behavior suggests that the sediment flux is supply limited. We interpret that much of the sediment is subglacially derived, and its transport into the river network is restricted either by limited bedrock erosion or subglacial hydrology.

Plateau Building and Erosion: the role of large rivers in the evolution of relief in active orogens

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When and how Tibet became the highest and largest continental plateau on Earth remains a puzzle. Both the mechanisms and timing of uplift are hotly debated. Unraveling jointly river development and tectonics is the key to understand processes of landform evolution and continental plateau building. Here we show how surface processes such as erosion and sediment transport by large rivers interacting with actively growing ranges within or outside Tibet play a leading role in shaping the landscape of the plateau.

In northeastern Tibet, ongoing crustal shortening, together with sediment infill of basins that are either internally drained or partially drained by the Huang He (Yellow River), attest to a process of plateau growth and elevation increase during the Plio-Quaternary. The current upper course of the Yellow River, for instance, which lies in the transition zone between southern monsoonal influence and northern arid Central-Asia, results from a relatively stable regime in which the river evolves from a state of disjointed lake-filled basins to a state with a continuously draining channel. The rates of river incision (2-6 mm/yr) and tectonic uplift (1-3 mm/yr) measured through cosmogenic nuclide dating show that the transition from one state to the other can occur rapidly (last lake high-stands around 120-250 ka), corroborating active Plio-Quaternary plateau growth via incorporation of sedimentary basins into the northeastern part of the plateau. At the scale of the entire plateau, the maxima of the hypsographic curve are associated with high, elevated plains and may have formed by a similar mechanism, involving debris infilling of closed basins - and relief smoothing by internal deposition - upstream from coeval, tectonically rising mountain ranges.

In southeast Tibet, by contrast, current fast river incision (5-7 mm/yr), as documented along the Jinsha (Yangtse) river gorge, attests to rapid headwater retreat and down-cutting into a previously high-elevation plateau surface. The smooth plateau morphology is now being destroyed and dissected, while river incision is responsible for regional relief increase. These results indicate recent and rapid changes of river evolution in Tibet, and coupling between fluvial dynamic, tectonics and climate in shaping both the interior and the edges of the Tibetan plateau. It is likely that most orogenic plateaus on the planet owe their high, flat morphology to such coupling.

Impact of late-Cainozoic climate change on relief development and orogen dynamics

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Over the last two decades, the geoscience community has realized that surface erosion, considered for over a century to respond passively to tectonic forcing, in fact strongly interacts with tectonic processes to produce the variety of deformation styles and relief forms observed in nature. Multiple feedbacks between tectonics, climate and erosion have been identified. In particular, it has been proposed that Cainozoic uplift of mountain belts such as the Himalaya led to global cooling due to CO_2 drawdown from the atmosphere by efficient weathering reactions (a mechanism already proposed by Ebelmen in the 19th century) and organic carbon burial[1,2]. At the same time, however, late-Cainozoic climate change, characterized by overall cooling and increased climatic variability, has been suggested to be responsible for increased erosion rates[3,4] as well as uplift of mountain peaks through the isostatic response to erosion[5,6]. Spatial variations in climate, such as orographic precipitation, appear to exert a significant control on the tectonic style of orogens[7,8], while some active mountain belts have also been argued to respond to late-Cainozoic climate change by tectonic reorganisation[9-11].

Pliocene-Pleistocene (post-5 Ma) increases in sediment flux have been reported from many major mountain belts such as the Himalaya[12] and the European Alps[13]. It has been suggested this is a global signal[3] in response to increased climatic instability since the Pliocene[4], although recent work suggests that at least part of the signal may be intrinsic to the nature of the sedimentary record[14,15]. An initial analysis of *in-situ* thermochronology data from the Alps appeared to support the Pliocene increase in erosion rates[16], which have been linked to increased precipitation subsequent to the Messinian Salinity Crisis[9] and/or the onset of Gulf-Stream circulation[17]. However, recent more detailed work, based on numerical inverse modelling and the use of new high-resolution thermochronometers, suggests locally decreasing erosion rates during that time[18,19], while detrital thermochronology from the basins surrounding the Alps suggests little change in erosion rates on the orogen scale[20,21]. Thus, the imprint of Pliocene climatic variations on mountain-belt erosion and tectonic development (e.g., [9]) may have been overstated and the sediment-flux data that suggested a strong link may require re-examination.

In contrast, the new data imply a significant increase in relief through focussed valley incision since mid-Pleistocene times (~1 Ma)[18,19], which can be related to efficient but highly localised glacial erosion, due to extensive glaciation of the Alps triggered by the mid-Pleistocene climate transition[22-24]. The isostatic response to a significant increase in Alpine relief due to glacial valley carving may explain part of the surprisingly high measured geodetic uplift rates in the western Alps[25] and may also contribute to the current extensional deformation observed within the core of the mountain belt. In the tectonically much more active southern Alaskan orogen, a major tectonic reorganisation of the belt at ~1 Ma has been proposed to occur in response to increased glacial erosion since the mid-Pleistocene climate transition[10]. Thus, it appears that this recent climatic change had a significant impact on mountain belts by enabling more focussed and efficient glacial erosion of topography. Confirmation of this hypothesis awaits more detailed analyses of the recent erosional, relief and tectonic history of glaciated mountain belts worldwide (e.g., [26]).

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Dynamic vegetation modelling and its importance to study weathering processes and related climate feedbacks

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Continental vegetation is thought to have significant impacts on rock weathering rates. The organic matter produced by vegetation is decomposed in the surface layers of the soil and produces CO_2 and organic acids that lower the pH of soil water and thus favour chemical weathering. Vegetation also impacts the soil hydrological budget through many processes, of which precipitation interception, uptake of soil water by the roots followed by transpiration, modification of the energy budget (changes in albedo and roughness length), production of channels along roots that enable water percolation, etc. These processes alter the runoff rate, one of the most important parameters controlling weathering. Vegetation finally influences physical weathering rates, increasing it through the pressure exerted by the roots on the rock structure or reducing it through stabilisation of the soil surface. Geochemical models that describe weathering incorporate some of these processes, but generally in a very crude way, mostly through simple empirical relationships. Climate change in the past has strongly altered vegetation distribution and net primary productivity and this can also be expected for the future. How would such changes alter weathering? What are the feedback processes involved in the vegetation-soil-weathering complex? What are the implications for the strength of the carbon cycle feedbacks on the climate system? To answer these questions, it is necessary to implement a mechanistic link between vegetation, soil water and weathering into models describing vegetation and weathering processes. Current dynamic vegetation models can be used to build this link. These models are able to describe the dynamics of vegetation and terrestrial carbon cycle in relation to climate change.

Here, we present two examples of the use of vegetation models for understanding chemical weathering processes and predicting their response to climate change. The first example is a study of carbonate rock weathering along an elevation (and temperature) gradient in the Jura Mountains in France. The second example is a projection of the impact of future climate change on the weathering rates of North American loess soils along the Mississippi River. Both studies emphasize the role of vegetation in controlling the response of weathering to climate parameters. In the Jura Mountains, it appears that the effect of vegetation and soil CO_2 (provided by root respiration and soil organic matter decomposition) are more important than the direct effect of temperature to explain the changes in carbonate weathering rates along the elevation gradient. The ASPECTS forest vegetation model allows explaining the trends observed in the river data. For Mississippi loess soils, the results of a fully transient simulation of the CARAIB dynamic vegetation model forced by climate scenarios from the ARPEGE model suggest that runoff will decrease over the 21st century in the studied area, especially in the most northern sites of the basin, because drought periods become more and more recurrent near the century. These scenarios are used to force the WiTCh catchment-scale weathering model. The results indicate a complex evolution of weathering rates in the future, resulting from the combined effects of the precise evolution of temperature, runoff and soil CO_2 production. For instance, at the northern sites, soil CO_2 partial pressure tend to decrease and soil water pH tend to rise leading to increase of the saturation index of several minerals, which tends to decrease weathering rates, but this may be compensated by the direct effect of the temperature rise on mineral dissolution or solubility. These results illustrate the complex nature of weathering and emphasize its close relationship with vegetation evolution.

Climate change and the future of continental weathering

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Continental weathering has been considered for long as a key process in the global carbon cycle at the geological timescale. Conversely, the evolution of the CO_2 sink by weathering is neglected in all studies dealing with the future of our climate, because weathering is considered as a slow process, almost inert at the secular time scale. However, recent data surveys have demonstrated the potential high sensitivity of weathering to the ongoing climate and land use changes[1,2].

According to future anthropogenic emission scenarios, the atmospheric CO_2 concentration may double before the end of 21st century, resulting in a global warming more than 6°C in the worse case. The global temperature increase will promote changes in the hydrologic cycle through redistributions of rainfall patterns and continental vegetation cover. All these changes will impact the chemical weathering of the continental rocks. To evaluate these impacts, we use a process-based model of the chemical weathering of the continental surfaces (B-WITCH[3], spatial resolution 1°x1°) forced by models describing the atmospheric general circulation and the dynamic of the vegetation under increased atmospheric CO_2. We focus on the arctic environment where land use changes can be neglected while the climate change is expected to be important (the Mackenzie watershed)[4]. We calculate that the CO_2 consumption flux related to weathering processes (including carbonate and silicate dissolution) may increase by more than 50% for an atmospheric CO_2 doubling for one of the most important arctic watershed: the Mackenzie River basin[4].

The response of the global carbon and alkalinity changes linked to the enhanced carbonate and silicate weathering under a future warmer climate is explored using a numerical climate-carbon model (GEOCLIM[5]). The objective is to address the timing of the carbon storage in the ocean and the response of the carbonate deposition on the seafloor.

Our study stresses the potential role that weathering may play in the evolution of the global carbon cycle over the next centuries.

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Biogeochemistry of major and trace elements in the watersheds of the Arctic Ocean basin: the change of fluxes, sources and mechanisms under the climate warming prospective

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Warming of the permafrost accompanied by thaw and the release of ancient organic carbon is one of the most significant environmental threats within the global climate change scenario. While the main sites of permafrost carbon processing and its release to the atmosphere are thermokarst (thaw) lakes and ponds, the main carriers of carbon and related major and trace elements from the land to the Arctic Ocean are Russian subarctic rivers. This multidisciplinary study describes results of more than a decade of observations and measurements of elements fluxes, stocks and mechanisms in the Russian boreal and subarctic zone, from Karelia region to the Kamchatka peninsula, along the gradient of permafrost-free terrain to continuous permafrost settings, developed on various lithology and vegetation coverage. We offer a new, geochemical-based look on the functioning of aquatic boreal systems which quantifies the role of the following factors on riverine element fluxes: 1) the specificity of lithological substrate; 2) the importance of colloidal forms, notably during the spring flood; 3) the phenomenon of lakes seasonal overturn; 4) the role of permafrost presence within the small and large watersheds and 4) the governing role of terrestrial vegetation in element mobilization from rock substrate to the rivers. Care of such a multiple approach, a first order prediction of element stocks and evolution under scenario of progressive warming in high latitudes becomes possible. It follows that the increase of the thawing of frozen peat in Western Siberia will increase the stocks of elements in

surface waters by a factor of 3 to 10 whereas the increase of the thickness of active layer, the biomass and the primary productivity all over permafrost-affected zone will bring about a short-term increase of elements stocks in labile reservoir (plant litter) and riverine fluxes by a factor of 2 to 3. While the climate warming will certainly affect the winter-time element fluxes and speciation, it is unlikely to change the nature and magnitude of colloidal fluxes to the ocean that occurs during several weeks of the spring flood.

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ACTIVITÉ ANTHROPIQUE ET ÉROSION

ANTHROPOGENIC ACTIVITY AND EROSION

Sustaining Soil at the Heart of Earth's Critical Zone

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Growth in human population and wealth is expected to double the global demand for food and fuel and increase by 50% the demand for clean water by 2050. This will occur as humanity must act to mitigate and adapt to climate change. These drivers of environmental change are putting increasing pressure on Earth's soils and their ability to deliver essential goods and services. New policy such as the EU Thematic Strategy for Soil Protection recognises these threats and urges new research to find interdisciplinary solutions. The SoilTrEC project funded by the European Commission draws on the methodology of Critical Zone Observatories (CZOs) to focus a critical mass of international, multi-disciplinary expertise to tackle the challenge of sustaining soil and preventing and reversing its degradation. The research hypothesis is that soil functions exhibit a cradle-to-cradle life cycle. Four SoilTrEC CZOs are located along a hypothesised life cycle of soil functions; from incipient soil formation, through productive use of arable and forested land, to highly degraded soils that have experienced millennia of intensive land use. Further CZOs have been selected totest soil process models that represent the stages of the soil life cycle. Key results focus on the central role of soil structure and soil aggregate formation in soil processes and functions. Research methods include detailed analysis and mathematical modelling of soil properties related to aggregate formation and their relation to key processes of reactive transport, nutrient transformation and carbon and food web dynamics in soil ecosystems. This programme of research also tackles how to quantify the monetary valuation of soil within its life cycle. Further experimental design at global scale is proposed to study soil functions along planetary-scale environmental gradients. This would allow scientists to gain insight into the responses of soil processes to the increasing human pressures on Earth's Critical Zone that arise through rapidly changing land use and climate.

Impact of agriculture on the chemical weathering of silicates

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Although Si is generally not considered as a nutrient for terrestrial plant, it can be taken up in large amounts by plants, especially grasses. Recent studies have suggested that land use and particularly agriculture can modify the Si cycle. Although these assumptions are mostly based on masse balances calculated at the watershed scale, there are also indications of depletion of soil available Si in soils cropped with cereals.

The assessment of the extent of the perturbation, its impact on the plant cycle and food production and its resilience is challenging and requires a better assessment of the mechanisms responsible for acquisition of Si by plant (e.g. identification of the parameters controlling Si bioavailability to plants). Very generally Si accumulated in plants originates from the dissolution of various soil silicates, which respective contributions are not clearly defined. Plants take up from the soil solution where Si is mostly present as the neutral molecule $Si(OH)_4$ (silicic acid). $Si(OH)_4$ is absorbed by the roots by a mechanism that is not fully understood and is polymerized in shoots through the elimination of water by evaporation, eventually building up phytoliths (amorphous opaline silica particles). Because isotopic tracing is not possible for Si, steady state models have been developed to quantity Si turnover. They show that plants absorb a significant fraction of dissolved Si that originates from phytoliths returning to soil during litterfall decomposition. Laboratory experiments show also that phytoliths are a source of silica amongst the most soluble of the soil minerals at slightly acid to neutral pH. However, because the concentration of phytoliths in soil is generally low (below 10 mg/g), the contribution of other soil silicates such as clay minerals as a source of bioavailable silica could be crucial in soils where highly soluble primary silicates have been exhausted and phytoliths depleted or not accessible. In addition, Si acquisition in acidic environments, where phytoliths have a limited solubility is poorly documented.

We propose an up-to-date synopsis on Si cycle in terrestrial ecosystems and, based on literature and original results, we discuss the importance of the various parameters controlling Si uptake by plants.

Evidence of short-term clay evolution in soils under human impact

Evolution rapide des argiles des sols sous l'impact des activités humaines

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Clay minerals are still often considered as stable in soils over a century to millennium time scale despite few examples of rapid evolutions. Indeed recent advances in X-ray diffraction pattern treatment combined with studies of soil sequences designed to evidence changes in soil due to agriculture or land uses, on time scales ranging from a few decades to a century, demonstrated that changes in clay mineralogy were faster than commonly thought. In this paper we present (1) one principle of clay X-ray diffraction pattern decomposition and the possibility it brought in terms of identification of changes in soil clay mineralogy; (2) the evidences of rapid clay evolutions (interfoliar ion exchanges, weathering or transport) based on studies of soil sequences; (3) the ongoing development in X-ray diffraction analysis and their potential consequences in terms of clay mineral quantification.

Key-words:

Mineralogy, pedogenesis, human impact, reactivity, short time evolution

Les minéraux argileux sont généralement considérés comme stables dans les sols à l'échelle du siècle ou du millénaire et ce, malgré des exemples d'évolution rapide ces minéraux. Des développements récents dans le traitement des diffractogrammes des rayons X, acquis sur des séquences de sols, mettent en évidence des évolutions des minéraux argileux suite à des changement d'usage des terres ou de pratiques agricoles sur des pas de temps allant de quelques dizaines d'années au siècle. Dans ce papier, nous présentons (1) l'apport de la décomposition des diffractogrammes de rayons X pour déterminer les changements de la minéralogie des argiles dans les sols ; (2) des exemples d'évolutions rapides des argiles dans les sols (changement de cation interfoliaire, altération ou transfert) ; (3) l'apport des développements en cours sur l'analyses des diffractogrammes de rayons X pour améliorer la quantification des minéraux argileux des sols.

Mots clé:

Minéralogie, pédogenèse, impact de l'homme, réactivité, évolution à court terme