
Bruce Velde · Alain Meunier

The Origin of Clay Minerals in Soils and Weathered Rocks

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With 195 Figures and 23 Tables

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Authors

Bruce Velde

Ecole Normale Supérieure (ENS)
Département Terre-Atmosphère-Océan
Laboratoire de Géologie
24, rue Lhomond
75231 Paris Cedex 05, France
E-Mail: velde@geologie.ens.fr

Alain Meunier

Université de Poitiers
UMR 6532 HydrASA – Bâtiment Géologie
40, Avenue du Recteur Pineau
86022 Poitiers Cedex, France
E-Mail: alain.meunier@univ-poitiers.fr

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Preface

Of course such a book as we propose here is not the product of just two people working together, although the experience has been a great pleasure for us. We would like to thank our many collaborators and students who have encouraged our effort by their, often, sharp criticism. We hope that we have used their comments to good effect. Especially we would like to thank Pierre Barré for his help, enthusiasm and consent for the use of much of his thesis material in formulating the last chapter of the book. Dominique Righi was instrumental in giving us ideas, useful comments and vigorous debate for a great number of our ideas and during the periods of formulation of our conclusions. Our approach is from mineral chemistry and hence has greatly benefited from discussions with people who know soils and plants. The project of this book was realized and encouraged with the help of Wolfgang Engel who, unfortunately is not with us to see its finalization. We greatly regret his passing.

This book is not in the general pattern of accepted knowledge and analysis of the phenomena which affect the occurrence of clays in the surface environment. We stress the role of plants at the bio-interface and the importance of microsystems at the water/rock interface. We believe that the literature at our and anyone's disposal shows that the system of clay formation and reaction is highly dynamic, especially at the surface. Clay alteration profiles are slow to form, thousands to hundreds of thousands of years, but they react quickly at the surface to chemical change, essentially engendered by plants. This is the message. Clays can react in short periods, years to tens of years, and hence should be considered as part of the active surface environment. Land use can be impacted by management for periods as short as those of elected officials in governments. Thus soil scientists and ecologists can forcefully argue for better management on a year to year basis and the results can be shown within the period of an appointed official's term. Therefore a clear understanding of plant and soil interactions and the fundamental alteration processes is vital to stewardship of one of the most precious parts of nature, the soil zone.

We hope that this book and some of the ideas presented will inspire young people to look more closely at the surface environment in a quest for a more rational and viable use of soils. Surface clay minerals appear to react very rapidly to changes in environments, specifically changes in plant regime in soils. The high reactivity of this kind makes clay minerals potential indicators of changes in the Earth's surface paleo-conditions and those engendered by the action of agricultural man.

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Introduction

As outlined in Chap. 1, clays are historically considered to be formed of $<2\ \mu\text{m}$ particles. The use of the optical microscope for petrographic observations at the end of the 19th century defined the limit of a recognizable crystal and mineral. Crystals whose size was lower than the resolution of the optical microscope, $2\ \mu\text{m}$, were unidentifiable and called clays. Because of this size-dependent definition, clays include different mineral species: silicates, oxides, carbonates. The largest part of the material of our investigation is called a phyllosilicate, i.e. silicate material which has a sheet like aspect, thinner than long and large. However such materials which are found in the small grain size fraction, though most often of small size, can at times reach several tens of micrometers in diameter. The same types of mineral can be found as high-temperature phyllosilicate equivalents, minerals such as micas and chlorites which can be found in centimetric sizes. Thus size is not a definite description of the silicate minerals found and formed at the Earth's surface. In a very general manner, one can say that phyllosilicates of high temperature origin, greater than $40\ ^\circ\text{C}$, are of diagenetic or metamorphic origin and are not stable under surface conditions. They tend to interact chemically at conditions where atmospheric water is present. It remains for us to show the differences between clay minerals whose origin is at the Earth's surface and those formed under other conditions. The first identification of a surface clay mineral is that it has a small grain size, generally $<2\ \mu\text{m}$.

Even if the reasons for small crystal size which are constantly observed are not fully understood at present, it is certainly the major characteristic of surface clay minerals. Because small size induces very great crystal surfaces, most of the remarkable chemical and physical properties of clay minerals are related to surface interactions. This was discovered very early during the first ages of human technical development: the plasticity of water-clay mixtures which was exploited during the Neolithic period for the production of pottery. Soils, and consequently clay minerals, are the support of the most fundamental activities of mankind: agriculture, ceramics and housing. Even today about 40% of the Earth's inhabitants live in dwellings composed in part by earth, i.e. clay assemblages with other materials. Therefore, the question of the origin of clay minerals is as important as that of the origin of humanity. Clay minerals are hydrated silicates. They contain hydrogen assigned to OH groups which contribute to the electronic stability of the framework of the crystal lattice (Grim 1953). However, they often contain molecular water associated with cations located between the basic structural layers of the minerals. It is clear that hydrogen and hence water is essential for clay mineral formation. Generally speaking, clay minerals form from aqueous solutions interacting with other, pre-existing, silicate species by dissolution-recrystalliza-

tion processes. Thus, the origin of clay minerals is related to water-rock interactions. In order to understand the mechanisms of fluid-rock interactions it is important to determine the driving force of these reactions typical of Earth surface conditions. Particularly, the role of chemical potential gradients must be considered in order to determine the stability domains of each species of clay mineral. One should keep in mind that clay minerals are first of all minerals, that is to say solids, able to react to changes in the conditions of their environment. Such changes are classically described in burial diagenesis where surface alteration clays are progressively transformed into illitic ones under increasing burial conditions, i.e. changes in temperature.

The most important geological occurrence where clay minerals are formed is that of rock weathering and soil formation. However, one must not forget that clay minerals are formed under the influence of hydrothermal action, i.e. the interaction of water and rock at conditions below the Earth's surface. Here one major clay resource is that of kaolinite, a mineral which has been used in many different industrial applications. Further, one finds significant alteration (weathering) of ocean bottom basalts creating proto-clay minerals which act as a sink for potassium in ocean water transfer, leaving sodium as the major alkali present in the greatest surface zone of the Earth. Diagenetic alteration of volcanic ash forms a near mono-mineralic material called bentonite (smectite) which has received recent attention in use for waste repositories for radio-active materials. Thus, atmospheric interaction with rocks is not the only source of clay minerals. However, the most likely interaction that humans are likely to have with clays is with those formed under conditions near those of the human environment, alteration of rocks to form soils.

We would like to attempt an explanation of the interactions of silicate and water at the surface of the Earth in systems generally described as weathering. This is the site of surface clay mineral formation. Water is the major motor of reaction, allowing and engendering chemical change. The minerals formed are stable at low temperatures, probably below 40–80 °C compared to those present in diagenetic series. However, the rapid change of mineralogy, on a geological scale at least, indicates subtle changes in the mineral structure as determined by X-ray diffraction, the major identification tool for clay minerals. Such change is the result of different chemical equilibria. Our objective is to clarify the factors which engender the change and persistence of surface clay minerals. In order to do this it is useful to understand the specificity of clay mineral structures and chemistry. The second step is to determine the chemical variables found under surface conditions which can produce and act upon surface clay minerals once formed. If one understands the origin of surface clays, and their stabilities, it will be possible to use them to better advantage in the coming era of environmental awareness.