Are clay minerals a fundamental biogeochemical regulator of the biosphere at Earth system scales

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A common focus of clay mineralogists is on the properties of phyllosilicates that enhance chemical and manufacturing processes of materials, drilling or agricultural production. Less studied is the role that clay minerals play at global scales in Earth system processes regulating the biosphere. For example, one of the most critical processes on the Earth's surface is the long-term sequestration of organic carbon through burial. This provides an important sink of CO_2 drawn from the atmosphere and fixed by photosynthesis. This same reaction is also the primary source of free oxygen to the atmosphere, and for every mole of CO_2 fixed in to reduced (organic) carbon and buried in sediment, one mole of free oxygen is released to the atmosphere.

A strong association between enhanced carbon burial and mudstones is well known from the geological record. While mudstones contain a portion of clay minerals, the specific role these minerals may play in this process is not often considered. Recently, the surface area of mudstones in modern and ancient marine sediments has been shown to have a first order relation with organic carbon concentration. Since surface area is a function of clay mineralogy, the burial of carbon may be a closely related to specific clay minerals and their properties. As a working hypothesis, the abundant surface area of smectitic clay minerals are suggested to provide a critical control on enhanced carbon burial represented within conspicuous black shale deposits that occur episodically through the geologic record. These intervals have previously been attributed to oceanographic processes such as global oceanic anoxia, though a correlation between mineral surface area and total organic carbon in representative examples presented here may indicate a dominantly clay mineral control.

An association between specific clay minerals such as smectite and organic carbon burial and preservation has implications for behavior of the Earth system. This is because marine sediments are primarily composed of detrital clay minerals formed in soils and transported to marine environments by rivers before deposition. The mineralogy of clay minerals in marine sediments is thus a function of the hydrological conditions determined by continental climate and to some extent the protolith of continental rocks. This relation implies a potential feedback between changes in continental climate that influence clay mineral production and in turn carbon burial that controls CO_2 concentration in the atmosphere. This feedback has the potential to work on relatively rapid time scales of centuries or less as suggested by examples presented here.

A clay mineral influence on organic carbon also has implications for changes in the biosphere through time and may constrain the habitability of Earth by metazoan (oxygen utilizing) organisms. Since the amount of carbon buried (and thus oxygen released) is related to the amount of mineral surface area in modern sediments, then a reduction in surface area implies a reduction in oxygen flux to the atmosphere. It is likely that clay mineral production through most of the Precambrian was only a fraction of that occurring in the Paleozoic because of the limited soil development on land early in Earth's history. Continental surfaces were sterile or devoid of life through most of Earth's history, and it is only in the later part of the Precambrian that a record of simple single celled organisms, protists, liverworts, fungi and algae become evident as well as geochemical evidence for the greening of the continental surface. This coincides with an increase in phyllosilicate abundance in continental margin sediments as shown here. This increase can reasonably be attributed to organisms that produced the first soils that then increased clay mineral production and thus carbon burial potential. Evident steps in clay production were also likely associated with the radiation of vascular plants later in the Paleozoic.

Soils are the 'clay mineral factory' in the Earth system today, and play a critical role in directly storing carbon but also for producing clay minerals that can preserve carbon in continental margin (marine) sediments where the bulk of carbon is buried. Changes in climate and secular controls capable of influencing clay production provide a potentially important feedback to the Earth system via carbon burial that controls CO_2 as well as free oxygen production. Not only do clay minerals thus represent an unrecognized feedback on climate change, but they may be attributed to the appearance and radiation of oxygen utilizing organisms (animals) on Earth.