Clay mineral evolution

ROBERT M. HAZEN1,2,*, DIMITRI A. SVERJENSKY1,2, DAVID AZZOLINI3, DAVID L. BISH4, STEPHEN C. ELMORE2, LINDA HINNOV3 AND RALPH E. MILLIKEN5

1Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Road NW, Washington, D.C. 20015, U.S.A.
2Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Road NW, Washington, D.C. 20015, U.S.A.
3Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland 21218, U.S.A.
4Department of Geological Sciences, Indiana University 1001 E. 10th Street, Bloomington, Indiana 47405, U.S.A.
5Department of Geological Sciences, Brown University, Box 1864, Providence, Rhode Island 02912, U.S.A.

ABSTRACT

Changes in the mechanisms of formation and global distribution of phyllosilicate clay minerals through 4.567 Ga of planetary evolution in our solar system reflect evolving tectonic, geochemical, and biological processes. Clay minerals were absent prior to planetesimal formation ~4.6 billion years ago but today are abundant in all near-surface Earth environments. New clay mineral species and modes of clay mineral paragenesis occurred as a consequence of major events in Earth’s evolution—notably the formation of a mafic crust and oceans, the emergence of granite-rooted continents, the initiation of plate tectonics and subduction, the Great Oxidation Event, and the rise of the terrestrial biosphere. The changing character of clay minerals through time is thus an important part of Earth’s mineralogical history and exemplifies the principles of mineral evolution.

Keywords: Clay minerals, biominerals, weathering, diagenesis, Mars mineralogy

INTRODUCTION

The mineralogy of terrestrial planets, moons, and asteroids diversified as physical, chemical, and (in the case of Earth) biological processes modified the initially relatively homogeneous material of the solar nebula into differentiated zones of varied temperature, pressure, and composition. Earth’s 4.567 billion year history, as a consequence, can be divided into three eras and 10 stages of mineral evolution, each of which has seen significant changes in the planet’s near-surface mineralogy (Hazen et al. 2008, 2011; Table 1). These dramatic changes include diversification in the number of different mineral species; shifts in the distribution of those species; systematic changes in major, minor, and trace element compositions of minerals; and the appearance of new grain sizes, textures, and/or morphologies. The concept of mineral evolution thus places mineralogy in a dynamic historical context, in which different mineral species and mineralogical characteristics arose at different stages of planetary history as new modes of mineral paragenesis came into play. However, the initial presentation of this framework by Hazen et al. (2008) did not examine any one group of minerals in detail. Here we consider the important case of the evolution of phyllosilicate clay minerals, which, possibly more than any other mineral groups, exemplify the connections among the geosphere, hydrosphere, and biosphere (Elmore 2009).

It is likely that no phyllosilicate clay minerals were present in the pre-solar molecular cloud, which contained approximately a dozen micro- and nanoscale refractory “ur-minerals” (Hazen et al. 2008). Yet, although clay minerals were absent during the initial high-temperature stages of planet formation, they now represent an important component of the near-surface crustal environment of Earth, Mars, and the parent bodies of carbonaceous chondrite meteorites. They also represent perhaps the most important class of minerals with which mankind interacts on a daily basis. Therefore, understanding the evolution of clay minerals as products of physical, chemical, and biological alteration processes is critical for understanding the mineralogical history of Earth and other worlds. Indeed, clay minerals provide a revealing case study for Earth’s changing mineralogy through time for at least six reasons: (1) clay minerals first appeared in the early stages of planetary accretion and have been ubiquitous near-surface phases throughout our planet’s history; (2) the 10 groups and more than 50 species of phyllosilicate clay minerals officially recognized by the International Mineralogical Association arise through varied paragenetic modes that parallel changing near-surface conditions and processes; (3) all of the principal clay mineral structure types are compositionally adaptable with diverse cations in tetrahedral, octahedral, and interlayer sites. Therefore, major, minor, and trace elements are likely to have varied systematically through time and thus reflect changing near-surface conditions, including compositions of parent rocks, solution chemistry, and redox state; (4) clay minerals exemplify mineralogical feedback mechanisms: for example, some clay minerals strongly interact with organic molecules, so sedimentary burial of clay minerals can sequester reduced carbon and thus enhance atmospheric oxidation (e.g., Berner 2004), which in turn affects the nature and rate of clay mineral formation; (5) clay minerals have played a significant role...