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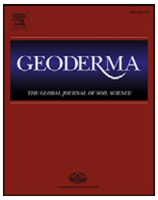

Soil genesis and mineralogy across a volcanic lithosequence

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ABSTRACT

Lithology is a principle state factor of soil formation, interacting with climate, organisms, topography and time to define pedogenesis. A lithosequence of extrusive igneous lithologies (rhyolite obsidian, dacite, andesite and basalt) was identified in the Clear Lake Volcanic Field in the Coast Range of northern California to determine the effects of lithology on pedogenesis, clay mineralogy and soil physiochemical properties. Based on regional landscape erosion rates (0.2–0.5 mm yr^{-1}), the soil residence times for the investigated pedons (~150 cm deep) were of the order of 3000 to 7500 years indicating that the soils developed under the relatively stable Holocene mesic/xeric climate regime. Soils from all lithologies developed to a similar Xeralf taxonomy with remarkably consistent physiochemical properties. Although total (Fe_t) and dithionite-citrate extractable (Fe_d) iron concentrations diverged across lithologies, the degree of weathering as assessed by the Fe_d/Fe_t ratio was similar across the lithosequence. In spite of large differences in silica content of the parent materials, the clay mineralogical assemblage of all lithologies was dominated by kaolin minerals (kaolinite and/or halloysite). All pedons displayed an increase in halloysite and the degree of halloysite hydration with increasing depth, except the basalt pedon, which was dominated by kaolinite with only trace halloysite. We attribute this lack of halloysite in the basalt pedon to the lower silica activities associated with this silica-poor lithology. There was a lack of nanocrystalline minerals across all lithologies as inferred from selective dissolution. The dominance of crystalline materials is a function of the xeric soil moisture regime whereby summer soil profile desiccation promotes dehydration and crystallization of metastable nanocrystalline precursors. Further, the pronounced summer dry period results in dehydration of halloysite (1.0 nm) to halloysite (0.7 nm; also referred to as meta halloysite in some literature), together with transformation to kaolinite, in the upper soil profile. In spite of the relatively young soil residence times of these soils (Holocene age), the effects of lithology persisted only in differences in Fe oxide concentrations (Fe_d), as well as a lack of significant halloysite in basalt pedons. The overwhelming effect of climate in these highly weatherable parent materials narrowed the trajectory of pedogenesis, resulting in soils from contrasting lithologies converging on kaolin mineralogy, a lack of nanocrystalline constituents, and similar soil physiochemical properties.

1. Introduction

Lithology is a master variable of pedogenesis (Jenny, 1994). The interaction of lithology with other factors such as climate and biology is a chapter in the story of life on Earth (Lenton et al., 2012), influencing global climate (Chadwick et al., 1994), primary productivity (Morford et al., 2011), the distribution of plants (Hahm et al., 2014), and the genesis of soils (Jenny, 1994). Lithology is a dominant factor in the early stages of pedogenesis, and yet very few pure lithosequences have been investigated owing to the difficulty of constraining the other soil forming factors, particularly climate (Jenny, 1994). With time, and under the influence of climate, the effect of parent material on soil mineralogy and physiochemical properties is thought to diminish, although the time required for parent material effects to be subdued is uncertain (Chesworth, 1973). Here we present a novel, well-constrained volcanic lithosequence that spans the breadth of extrusive igneous (i.e. hard rock) lithologies (rhyolite, dacite, andesite and basalt) to investigate the influence of lithology on pedogenesis, soil physiochemical properties and clay mineralogy. Understanding the role of lithology in pedogenesis is important for soil survey, ecological/biogeochemical modeling, agronomy/soil fertility and land-use management.

Previous investigations of lithosequences have attributed differences in soil morphologic and physical attributes to lithology. Schaetzl (1991) noted the influence of coarse fragments and texture on pedogenesis and plant distribution. Parsons and Herriman (1975) concluded that differences in grain size between schist, granite and pyroclastic materials contributed to differences in soil physiochemical properties and

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morphology. In Greece, soils in marble and dacite were finer textured, while soils in gneiss, granite and diorite were coarser textured (Yassoglou et al., 1969). Similarly, differences in soil texture and erodability were observed in soils in the Sierra Nevada of California formed in granodiorite, quartzite and basalt (Willen, 1965). These studies attributed many of the physical differences observed in soils to differences in the initial grain size of the parent materials; however, all these studies lacked investigations of clay mineralogy.

Within the few lithosequences that have included investigations of clay mineralogy, no clear trends of lithologic influence on clay mineralogy were identified. Hoyum and Hajek (1979) identified mixtures of smectitic and halloysitic clays in soils formed in coastal plain sediments, with halloysite in common to all soils, whereas Hutton (1951) concluded that the common weathering environment resulted in the dominance of smectitic clays in a loess climo-lithosequence. Anderson et al. (1975) observed predominantly smectitic clays in soils on limestone, and kaolinitic clays in soils on sandstone, likely due to differences in carbonates, pH, base cation content, and drainage. Levine et al. (1989) concluded that more permeable dolomitic limestone encouraged the formation of smectite through the dissolution of dolomite and release of Mg, while impervious limestone limited smectite formation. Mareschal et al. (2015) investigated soils formed in granites with differing grain sizes, and found differences in particle size, cation exchange capacity (CEC), and extractable Fe and Al, but not clay mineralogy. Similarly, Yousefifard et al. (2015), investigated a lithosequence including intrusive igneous rocks (granites and diorites) and extrusive igneous rocks (andesites and a dacite), and found differences in soil physicochemical properties, but no significant differences in clay mineralogy (smectite), which the authors attributed to the common arid/semiarid climate. Alternatively, Heckman and Rasmussen (2011) found vast differences in CEC, clay content and Fe-oxides, as well as clay mineralogy and mass flux, between rhyolite and basalt. Of these lithosequences, no consistent trends were evident for the influence of lithology on clay mineral formation. Furthermore, none of these lithosequences contained exclusive investigations of intrusive or extrusive igneous lithologies, and none spanned the range of silica compositions from felsic to mafic inclusively.

In contrast to previous findings on lithosequences that suggest divergence in clay mineralogy and soil physical and morphologic factors, climosequences in the mesic/xeric climate of California point to similarities in morphology and clay mineralogy in climatic zones of intense weathering, where the trajectory of pedogenesis appears to be narrowed due to the overwhelming influence of climate. Climosequences in basalt (Rasmussen et al., 2010), andesite (Takahashi et al., 1993; Rasmussen et al., 2007) and granite (Dahlgren et al., 1997a) identified zones of intense weathering at similar elevations and climates (mesic/xeric) where mild wet winters, and dry hot summers favor desilication, clay generation and illuviation, and crystalline phyllosilicate and Fe-oxide clay minerals.

To address these contrasting findings from lithosequences and climosequences, a well-constrained lithosequence of extrusive igneous materials that spans the range of felsic (rhyolite) to mafic (basalt) lithologies was identified in the Clear Lake Volcanic Field in the northern Coast Range of California. All lithologies were located in relatively close geographic proximity (within a 15 km radius) and the soils are believed to have primarily developed under Holocene climate conditions consisting of a mesic/xeric, temperature/moisture regime, with similar rates of denudation. Factors such as climate and soil residence time are relatively well constrained. By maintaining other pedogenic state factors constant, while varying the elemental composition of the parent material, this investigation seeks to identify the influence of lithologic composition on soil genesis, clay mineralogy, Fe-oxide generation, and soil physiochemical properties.

2. Materials and methods

2.1. Site description

The volcanic lithosequence is located within the Clear Lake Volcanic Field (CLVF), an active, late Pleistocene volcanic center in the northern California Coast Range, where regional deformation associated with the San Andreas Fault activates mafic to felsic eruptions (Fig. 1) (Hearn et al., 1975, 1995). The CLVF consists of a range of lithologies (rhyolite to basalt) in a complex of domes, flows and pyroclastic deposits (Hearn et al., 1975; Donnelly-Nolan et al., 1981). Four pedons were investigated from four lithologies of diverse chemical composition, but similar hard rock physical composition derived from flows in the CLVF, namely rhyolitic obsidian, dacite, andesite and basalt, all coexisting in the same climate and having a similar porphyritic character. The SiO_2 content of parent materials ranged from 55% in the basalt to 75% in the rhyolite (Hearn et al., 1995). Mean landscape erosion rates in the area are 0.2–0.5 mm yr^{-1} and uplift rates are ~0.3 mm yr^{-1}, corresponding to soil residence times for a 150-cm deep pedon of 3000 to 7500 years (Balco et al., 2013). These residence times constrain pedogenesis to relatively stable Holocene climate conditions. The climate is Mediterranean (xeric soil moisture regime, Soil Survey Staff, 2014a), with mild wet winters and warm dry summers. The mean annual soil temperatures are between 14 and 16 °C (mesic/thermic boundary, soil temperature regime, Soil Survey Staff, 2014a) and mean annual precipitation is ~640 mm, mostly occurring as rainfall in November to March. The dominant vegetation community at all sites was oak woodland (*Quercus – douglasii, kelloggii, wislizeni*) with minor pine (*Pinus - ponderosa, sabiniana*), and with annual grasses in the understory, with some recent conversion to winegrape production. Following fire, which has an average historical return frequency of 0–35 years for low severity fires, a chaparral shrub community dominated by *Quercus dumosa*, *Ceanothus* spp., *Arctostaphylos* spp., and *Adenostoma fasciculatum* is a common plant community. All sampling sites were on shoulder positions, with similar slope (15–20%) and aspect (southern).

2.2. Soil characterization

Soils were described in the field, sampled by genetic horizon, air-dried and sieved to isolate the <2-mm fraction. Soils were size fractionated using pipette and wet sieving methods (Soil Survey Staff, 2014b). Briefly, 10 g of air-dried soil were pretreated with 5% H_2O_2 for organic matter removal (Soil Survey Staff, 2014b), citrate-dithionite for Fe-oxide removal (Holmgren, 1967) and then dispersed with dilute sodium hexametaphosphate. Dispersed samples were wet sieved through a 53 μm screen, and the clay and silt (<53 μm fraction) collected for subsequent pipette analysis. Sands (>53 μm) were collected, dried at 105 °C, and weighed.

Soil pH was measured 1:2 soil:solution in H_2O, 0.01 M $CaCl_2$, and 1.0 M KCl (Soil Survey Staff, 2014b). Organic C and N were measured on ground samples (<125 μm) with an ECS 4010 CHNSO Analyzer (Costech Analytical Technologies, Inc., California, USA). Phosphate retention was determined using the method of Blakemore et al. (1981). CEC and extractable cations were measured with 1 M NH_4OAc (pH 7.0) extraction (Soil Survey Staff, 2014b). Base saturation was calculated from the sum of bases extracted by 1 M NH_4OAc. Pedon Fe_d, clay, and organic carbon pools (kg m^{-2}) for the upper 120 cm of each pedon were calculated based on field estimations of coarse fragment volume and bulk density estimates of 1.2 g cm^{-3} for A horizons, 1.3 g cm^{-3} for AB horizons and 1.5 g cm^{-3} for B horizons obtained from NRCS soil survey pedon description data.

2.3. Mineralogical analysis

X-ray diffraction (XRD) was performed on the clay-size fraction (<2 μm). XRD analyses were made with a Rigaku Ultima IV (Rigaku,