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# GEOLOGY AND GEOTECHNICAL ASPECTS OF THE IONE FORMATION

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## Ione Formation Field Trip

## TABLE OF CONTENTS

AEG-GRA

1995 Annual Meeting
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# Ione Formation Field Trip

## Geology of the Eocene Ione Formation, Ione Area, California

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## INTRODUCTION

The Ione Formation is an early to middle Eocene (Domengine) sequence of clastic sedimentary rocks that crops out along the western foothills of the Sierra Nevada mountains in California. Exposures of the Ione Fm. extend for over 300 km (200 mi.) between Oroville and Fresno (Figure 1, Appendix A) and are characterized by kaolinitic sandstones and mudstones with interbedded lignite. These sediments were primarily deposited in fluvial, deltaic, and marginal marine settings at the western margin of an Eocene landscape of low relief now occupied by the Sierra Nevada mountains. The Ione sedimentary system also included proximal fluvial channel deposits located in the Sierran foothills to the east and marine sediments in the subsurface in the Sacramento Basin to the west.

The mineralogical composition of the Ione Formation consists predominantly of kaolinite and quartz. This mineralogical assemblage developed in response to a unique set of Eocene geologic conditions that included long term continental stability associated with tropical weathering, followed by an erosional period initiated by tectonic uplift and changing base level. To fully understand the origin and occurrence of these unique kaolinitic sediments, one must consider all the components of the Ione depositional system, including sediment provenance, climate, depositional facies, and tectonic setting. While such a comprehensive study is beyond the scope of this guidebook, Wood (1994) presents a very detailed discussion of these factors. The information presented below draws heavily from Wood's study, and, in addition, includes new data that the authors' have obtained since Wood's initial report.

## GEOLOGIC BACKGROUND

### Basement Rocks

The regional stratigraphy in the vicinity of Ione can be subdivided into two basic groups—the Jurassic basement rocks of the folded north-south trending metamorphic belt and the Tertiary and younger clastic rocks that form a gently dipping veneer over the top. The Western fault block (i.e., west of the Melones fault zone) of the foothills metamorphic belt is comprised of three major units of Late Jurassic age. The oldest is the Gopher Ridge volcanics which crops out both west and north of the city of Ione (Figure 2). The younger two units, the Salt Springs slate and the Copper Hill volcanics, occur east of Ione.

Greenstones of the Gopher Ridge volcanics are an important part of the geologic section at the field trip stop at Jones Butte. Greenstone outliers west of Ione form a system of low ridges that are separated from the western edge of the Sierra Nevada foothills by a 4–5 km wide trough (Figures 2 and 3). Outcrops of hard greenstone are hummocky and tree-covered with irregular "headlands" and "islands" of large green boulders or outcrops that project up through the overlying lateritic paleosol. The Gopher Ridge volcanics represent pyroclastic and lava flows originally of andesitic composition (Clark, 1964). Petrographic analysis of the greenstones at Jones Butte shows that these rocks were extrusive or shallow intrusive andesite and intrusive porphyritic quartz diorite (Bates, 1945). Clark (1964) reported the occurrence of submarine volcanic rocks in the Gopher Ridge volcanics near the Calaveras River; however, none have been reported in the Ione area. Although plagioclase and augite from the original mineral suite remain in some of the rocks, Bates (1945) found that the groundmass of these rocks is dominated by greenschist facies secondary minerals such as chlorite, epidote, clinozoisite, sericite and secondary quartz. The style of volcanism, lithology, and tectonic setting (i.e., sutured in a linear metamorphic belt) collectively suggest an andesitic island-arc setting adjacent to a subduction zone, analogous to the modern Aleutian or Indonesian volcanic island chains.

The Salt Springs Slate crops out in a continuous north-south band on the east side of the Ione Valley (Figure 2) and consists primarily of black sericitic shale with local graywacke, tuff, and conglomerate (Clark, 1964). Because of similar lithologies and ages, Bates (1945) originally mapped this unit as the Mariposa Slate; however, Clark (1964) reported that the sediments forming these rocks were deposited in different basins and, therefore, he mapped these as two distinct units. The unit overlies and interfingers with the Gopher Ridge volcanics.

## Pre-Ione Lateritic Soils

At Jones Butte the Jurassic greenstones are mantled by a thick (>30 m) weathered residuum of lateritic soil that developed on the paleosurface in the Early Tertiary (Figure 4B). This soil horizon extends into the subsurface to the east below the Ione Fm. and reappears mantling the Salt Springs Slate in the foothills to the east of Ione (Figure 3). In most occurrences, the red iron-rich zone of this lateritic soil is missing and the weathering horizon is characterized by white, yellowish, or mottled saprolitic slate ("lithomarge" of Allen, 1929). Although greenstone forms the parent material of the Jones Butte laterite, the primary mineralogy has been completely altered in the laterite and the soil mineral assemblage is largely composed of kaolinite and iron oxides. This weathered horizon has regional extent and is a readily mappable unit (Figure 4A).

Allen (1929) and other early workers who referred to the highly weathered soils mantling the bedrock underlying Ione fluvial deposits as "laterite", recognized the implication that a tropical climate was required for laterite development. Corroborative evidence of this postulated tropical climate was offered by MacGinitie (1941) and later Wolfe (1978) through paleobotanical studies of fossil folia preserved in Ione Fm. sediments. Both researchers concluded that a "tropical rain forest" plant association existed in the central Sierras during the early Eocene. They reported that the early Eocene Sierran climate was analogous to the present day climate in the tropical lowlands of southern Mexico with a mean annual temperature of 27°C (81°F) and average annual rainfall of >200 cm (84 in). Most of the rainfall occurs during the summer months and the winter has periodic dry spells.

Modern soils formed under conditions of tropical weathering commonly include Oxisols and Ultisols. Oxisols are highly weathered soil profiles in which all but the most resistant minerals alter to iron oxides and low-base clay minerals such as kaolinite and gibbsite (Figure 5). Climates favorable for Oxisol development are characterized by minimum mean annual temperatures of 22–25°C (72–77°F) and greater than 100 cm (40 in) of annual precipitation (Singer, 1979; Buol *et al.*, 1980). Buol *et al.* (1980) noted that these climatic regimes also have pronounced winter dry seasons and low month-to-month mean and diurnal temperature fluctuations. Wolfe (1978; 1985) reported that hot-wet climatic conditions (those that favor Oxisol development) existed throughout the mid-latitudes of North America during the Late Cretaceous–middle Eocene period and extended as far north as the latitude of present day Washington state (~57°N). The widespread occurrence of kaolinitic tropical soils at high latitudes in the Northern Hemisphere provides corroborative evidence of a prolonged period of global warming (Goldish, 1938; Parham, 1970; Nilsen and Kerr, 1978; Peterson and Abbott, 1979; Sigleo and Reinhardt, 1988).

The 10+ m red iron oxide-rich horizon in the Jones Butte paleosol meets both the mineralogical and chemical requirements of an oxic horizon (Wood, 1994; Soil Survey Staff, 1975). This red zone is characterized by iron oxide redoximorphic features such as pisolitic and mottled iron oxide concretions. The terms "laterite" or "Latosol" are loosely used to refer to these iron-rich horizons of Oxisols. Oxisols and their diagnostic oxic horizons require the longest period of time ($10^6$–$10^7$ years) of any soil type to develop (Birkeland, 1984). Thus, the Jones Butte paleosol and other Oxisols preserved throughout the Sierras began developing long before the Ione depositional period, perhaps as early as the Late Cretaceous at the onset of the warm climatic conditions that characterized the Early Tertiary.

Below the oxic horizon lies the saprolite zone—the other major horizon of an Oxisol. This is the portion of the weathering profile in which lithic materials are nearly completely altered to secondary clay minerals, but the original fabric of the precursor rock is preserved. "Saprolite" is equivalent to the term "lithomarge" used earlier by Allen (1929). The saprolite zone is usually pallid or white and can be 10–20 m thick. Allen (1929) reported that it is the saprolite horizon of lateritic soils that most often lies below Ione fluvial deposits. The upper oxic horizons were apparently stripped away by Ione fluvial scouring (Figure 3).

Most of the saprolite zone of the paleosol at Jones Butte remains buried. Although the entire profile is not exposed, Bates (1945) and Carlson and Clark (1954) estimated a total thickness of 30 m or more from subsurface data (Figure 4B). Both the tremendous thickness of this weathering profile and the resultant mineral suite associated with this highly weathered soil profile are good indicators of the severity and duration of chemical weathering involved in its formation.

## Pre-Ione Eocene Sediments

Pre-Ione clayey sediments underlie the lower Ione in the bottom of drill cores in the Buena Vista basin (Pask and Turner, 1952). These sediments were deposited during a long period of Early Tertiary tropical weathering based on the observation that the sediments both overlie weathered basement rocks and are themselves mantled by a significant weathering horizon at the contact with the overlying lower Ione sediments. The pre-Ione sediments are largely silty clays but minor sandy and conglomeratic beds occur in some of the cores. They also contain a much greater abundance of feldspar than the lower Ione, with biotite and chlorite common. Differential thermal analysis (DTA) shows that these sediments have a heterogeneous clay assemblage that includes smectite in addition to kaolinite (Pask and Turner, 1952). This unit may correlate with other pre-Ione sediments of similar composition in other localities reported by Allen (1929).

## Ione Formation

The Ione Formation is exposed at the surface over much of the Ione and Jackson Valleys. Turner (1894) defined the type section near the town of Ione, California. Allen (1929) restricted the Ione Fm. to sediments with kaolinitic quartzose sands and clays, excluding overlying rhyolitic tuff ("clay rock") that was originally included in the formation by Turner (1894). Allen (1929) noted a significant increase in feldspar content in the upper Ione sandstones in several localities, but didn't distinguish the feldspathic sediments as a separate member. Allen correlated these upper Ione sands with the upper proximal gravels mapped by Lindgren (1894), while the lower 150–180 m (500–600 ft) of kaolinitic quartzose Ione sands were correlated with Lindgren's quartzose deep gravels. MacGinitie (1941) reported that kaolinitic proximal Ione sediments near Nevada City are overlain by 30 m (100 ft) of feldspathic, biotitic sands. Based on these mineralogical differences, he reiterated Allen's (1929) suggested identification of upper and lower Ione members.

The mineralogical distinction of the upper and lower Ione Members also extends to their respective clay mineral assemblages (Pask and Turner, 1952; Wood, 1994). Lower Ione sediments are kaolinitic sandstones and mudstones with high quartz to feldspar ratios. The upper Ione member contains a significantly greater abundance of smectite relative to kaolinite, as well as feldspar, biotite, and chlorite. The upper member is separated from the lower member by an erosional unconformity (Pask and Turner, 1952; MacGinitie, 1941).

Lower Ione sandstones exposed in the Ione Valley are well sorted and medium- to fine-grained. The sandstones are commonly crossbedded and trace fossils are locally apparent. These sediments were probably deposited in westward flowing alluvial fan braided stream environments (Rodgers, 1986). Although the Lower Ione in the center of the Ione Valley is 200+ feet thick, on the flanks of the Ione Valley such as at Jones Butte, lower Ione sediments form only a thin veneer over the basement rocks (Figure 4B).

Upper Ione sediments are absent at Jones Butte and in the local vicinity of the town of Ione. Local occurrences of upper Ione sediments are found in the Jackson Valley south of Ione. Upper Ione sediments were either not deposited in the vicinity of Ione or were removed by Pleistocene erosion.

## Valley Springs Formation

Rhyolitic volcaniclastic deposits of ash, tuff, and volcanic breccia comprise the Valley Springs Fm. at Jones Butte. Deposition of the unit has been assigned to the Oligocene–Miocene period; however, evidence from deposits farther north in the Sierras suggests that rhyolitic volcanism began as early as latest Eocene in the Central Sierras (Yeend, 1974; Wood, 1994).

## Mehrton Formation

The Mehrton Fm. of Miocene age forms the upper 150 foot volcanic cap at Jones Butte. It is comprised of andesitic sandstone, siltstone, tuff, and breccia deposited in fluvial and debris flow settings (Bates, 1945).

## ORIGIN OF KAOLINITE IN THE IONE FORMATION

The Ione Fm. contains economic reserves of high quality kaolinite. Two fundamentally different hypotheses have been proposed for the genesis of these important clay deposits: 1, they are detrital in origin and reflect erosion of earlier kaolinitic paleosols (Allen, 1928; Pask and Turner, 1952; Wood, 1994); 2, they are diagenetic and developed in place from alteration of feldspar by post-depositional processes (Gillam, 1974; Rodgers, 1986). Allen (1929) proposed that Ione kaolinitic fluvial sediments were largely derived from the erosion of lateritic soils covering adjacent landscapes. A comparison of the micromorphology of kaolinite in these Sierran paleo-Oxisols with that of kaolinite in Ione fluvial sediments reveals numerous similarities in the microfabric of transported mudstone clasts to underlying paleosol features (Wood 1994).

### Micromorphological Clues

Five major micromorphological properties aid in the definition of the pedogenic origin of Ione kaolinitic sediments (Wood, 1994):

1. Diverse grain size and heterogeneous microfabric (Photo 1, Appendix B).
2. Presence of packing voids and pedogenic fractures in clay clasts (Photo 1, Appendix B).
3. Presence of sand-sized clay aggregates of oxic soil material (micropeds).
4. Heterogeneity in crystallite size of kaolinite within kaolinite aggregates.
5. Presence of pedogenic cements (siliceous and organic) that stabilize clay aggregates (Figures 11 & 12 ; Photo 2, Appendix B).

To these criteria, several additional observational features can be added that are useful for defining detrital mud in sandstones (Dickinson, 1970; Wilson and Pittman, 1977). The morphological criteria of these authors can be summarized as follows:

1. Clay aggregates have a low bulk density due to inherent microporosity. Therefore, detrital clay aggregate clasts should be coarser than associated quartz and feldspar grains [i.e., only if sorting is moderately good and the two constituents are hydrodynamically equivalent].
2. Detrital clay will deform by compression between adjacent framework grains upon compaction and will conform to adjacent grain boundaries.
3. Flame-like wisps of crushed [deformed] lithic fragments extend into narrowing orifices between undeformed rigid grains.
4. The internal fabric of lithic fragments deformed by plastic flow commonly conforms to the margins of confining rigid grains as concentric drape lines.
5. Large matrix-filled 'gaps' in the framework suggest pseudomatrix, and the suggestion is strengthened where each 'gap'-filling is semi-homogeneous but texturally distinct from other 'gaps'.

All of these features have been identified by Wood (1994) in the kaolinitic sandstones of the Ione Fm. (See exemplary photos in Appendix B).

The microfabric of the kaolinite that forms in the soil environment (pedogenic) is different than that of diagenetic kaolinite that fills open pores in sandstones as a result of feldspar dissolution. Pseudohexagonal platelets arranged as short stacks and vermicular forms characterize diagenetic kaolinite. The relatively homogeneous grain size distribution among crystallites of diagenetic kaolinite results in considerable microporosity. In contrast, the microfabric of pedogenic kaolinite is characterized by an aggregate microfabric comprised of coarse kaolinite particles enveloped by a relatively fine-grained kaolinite matrix. This particle arrangement adds stability to the clay aggregates comprising the fabric of lateritic soils.

Lateritic paleosols located near Nevada City and Friant immediately underlie Ione fluvial deposits and Ione conglomerates clearly contain clasts of eroded laterite with well-preserved pisolitic fabric, as well as other distinguishing microscopic components (Wood, 194).

Amorphous silica cements occur in the clay fabric of both the saprolite and oxic horizons of the lateritic soil at Nevada City. These amorphous silica cements are very difficult to detect with conventional analytical techniques (Brewer and Sleeman, 1969), but even in low quantities, can greatly stabilize the soil fabric (Singh and Gilkes,1993). No opal-A peak is apparent in XRD analysis of clay material from either the oxic or saprolite horizons of the paleosol at Nevada City (Figure 9). However, amorphous silica cement occurs in sufficient abundance in the kaolinitic saprolite of the lateritic soil near Friant that an opal-A peak appears in XRD analysis of the <0.5 µm size fraction (Figure 10). The appearance of an opal-A peak in XRD analysis indicates that amorphous silica may occur in amounts of up to 20% or more (Singh and Gilkes, 1993). Analysis of the kaolinite zones cemented with amorphous silica using infrared spectrometry shows that trace amounts of aromatic and aliphatic hydrocarbon compounds are associated with the amorphous silica. Such hydrocarbon compounds are typical components of humic acids that form as a byproduct of the degradation of organic matter in the peat horizon in humid soils. Such dissolved organo-siliceous compounds can form effective cements in the soil fabric upon gelling (Photo 2, Appendix B; Wood, 1994; Oades, 1989).

The implications of the kaolinitic mineralogy and the various micromorphological features of the clay fabric associated with these Tertiary Sierran lateritic soils are that during periods of significant erosion, enormous volumes of kaolinitic detritus would have been shed to regional Ione stream systems in the form of stabilized sand-sized clay clasts. The siliceous cements and aggregate microfabric of pedogenic kaolinite would probably have stabilized the kaolinite aggregate clasts sufficiently to facilitate their transport as bedload sediment in Ione streams.

## DESCRIPTION OF IONE DEPOSITS

### Paleosols (pre-Ione)

The paleosols at Jones Butte and Nevada City possess oxic horizons composed of kaolinite, halloysite, iron oxides, and quartz (Figures 7 & 8B). Iron oxide cement is typically organized in mottled masses and concretions of hematite and goethite. Pisolites at Jones Butte are cross-cut by fractures filled with white clay, which XRD analyses show to consist largely of dehydrated halloysite, in contrast to the more mixed kaolinite-halloysite-hematite mineral assemblage of the pisolites (Wood, 1994; Figures 7A & 7B). In the field, the fracture-filling material shows well developed slickensides. Gibbsite was not detected in the analysis of this paleosol, although Bates (1945) reported it in his analysis.

The mottled material below the pisolitic zone at Jones Butte is composed of kaolinite with goethite occurring in the pallid (light) segregations (Figure 7C) and hematite producing the red coloration in the darker zones (Figure 7D). Drill cores through the lateritic soil show a gradual transition of this mottled zone into saprolitic material and eventually into fresh greenstone (Allen, 1929).

The underlying saprolite horizon of pre-Ione paleosols is often completely leached of iron and appears pallid or white. Kaolinitized mica books and quartz retain their position in the original granitic fabric. Quartz is the only residual mineral apparent in XRD analysis (Fig 8A). Trace amounts of resistate heavy minerals, including muscovite, zircon and monazite are apparent in petrographic analysis (Wood, 1994). Thus, complete removal of feldspar and other readily weatherable minerals apparently occurred before erosion of the regional lateritic cover and ensuing deposition of the Ione Fm.

### Proximal Ione Fluvial Deposits

Proximal Ione deposits in the vicinity of Nevada City were derived from erosion of underlying lateritic paleosols (Wood, 1994). Kaolinite occurs as sand-sized aggregates that were transported as bedload sediment in the form of stabilized clay clasts. These clay clasts were squashed and formed pseudomatrix after deposition. Some of the kaolinitic sandstones appear reddish in outcrop suggesting that post-depositional weathering has occurred. However, traces of unaltered amphibole grains occur in some of these sandstones indicating that post-depositional weathering was slight. Petrographic analysis shows that the discoloration in outcrop is caused by goethite cement occurring only in association with the detrital clay aggregates. This suggests that the goethite cement was probably formed by the oxidation of the iron chelated with the amorphous silica that permeates the detrital clay clasts.

The post-depositional weathering of Ione fluvial sediments in alluvial storage on the flood plain (MacGinitie; 1941) probably had an important effect on the ultimate composition of Ione fluvial and deltaic sediments in distal areas. Several workers have shown that in modern tropical river systems the leaching of weatherable minerals in fluvial sediments while in alluvial storage on the flood plain is an important part of a sediment compositional maturing process (Franzinelli and Potter, 1983; Johnsson and Meade, 1990; Johnsson *et al.*, 1991). This process results in sediment whose composition is more quartzose than that initially supplied to the stream system. When channel migration reincorporates these quartzose sediments back into active fluvial transport, the resulting amalgamated sediments are diluted by the weathered sediments of quartzose composition. Consequently, with this weathering process working the entire length of the river system, the sediments at the river mouth are considerably more quartzose than in upper reaches.

Petrographic evidence also shows that in these weathered proximal Ione fluvial sandstones, no authigenic kaolinite is associated with the leached feldspar grains. In the shallow horizons in which minerals were dissolved by surface weathering, the solutes were carried away in the groundwater leachate and no clay precipitated in the secondary pores. Sediments in alluvial storage on the flood plain were probably exposed to the weathering effects of the tropical climate for $10^2$–$10^3$ years before they were either reworked by migrating channels or buried by subsequent fluvial deposits and removed from the effects of surface weathering. With this relatively brief residence time, it is doubtful that significant soil horizonation or clay developed due to weathering, although some pedogenic illuvial clay has been recognized in weathered proximal Ione sandstones (Wood, 1994). Therefore, the chemical weathering of proximal Ione fluvial sediments on the flood plain probably did not operate long enough for diagenetic kaolinite to form.

Upper Ione sediments occur in the Nevada City area MacGinitie, 1941; Pask and Turner, 1952) and are distinguished by their more complex clay and primary mineral assemblage. Detrital kaolinitized mica grains are common in lower Ione sediments. In contrast, the abundant "biotite" grains of the upper Ione sediments are altered to smectite (Wood, 1994). The contrasting clay mineral assemblages of lower and upper Ione sediments (i.e., kaolinite vs. smectite) is probably a reflection of a change in global climate (cooling) that occurred beginning at the early-middle Eocene boundary (Miller, 1991; Frakes et al., 1992).

## Ione Sediments in the Ione Area

**Clay Mineralogy.** Petrographic analysis of lower Ione sandstones sampled from Apricum Hill, Wallens Pit, the Old Sand Plant, Owens-Illinois Pit, Lanes, and Jones Butte shows that quartz and kaolinitic clay are the dominant constituents of all the sandstones exposed in the Ione area (Figures 13 & 14; Photo 3, Appendix B; Wood, 1994). These Ione sandstones also contain minor amounts of heavy minerals and trace amounts of weatherable minerals including mica, feldspar, and amphibole. Mudstones in the Ione area are also kaolinitic. XRD analysis shows that the clay deposit at Jones Butte known as the "Edwin Clay" and the clay bed "B6" in the Bacon Pit deposit are composed of kaolinite with only a trace amount of smectite (Figures 15 and 16). A mudstone deposit at Lanes (Figure 13) possesses a similar kaolinitic composition.

An interesting and dramatic mineralogical change occurs in the upper 10 m of clay in the Bacon Pit mudstone section. XRD analysis shows a gradual upward increase in the amount of smectite in the clay assemblage. While the "B6" bed at about 10 m below the top of the clay deposit contains a trace amount of smectite (Figure 16), the "B3" clay about 3 ms higher (-7 m), contains about 10% smectite (Figure 17). Higher, the "B2" clay (-5 m) contains about 15–20% smectite (Figure 17). Finally, the "M21" clay bed at the top of the Bacon Pit section contains approximately 30% smectite (Figure 17). Clay compositions were estimated using the computer modeling program, Newmod© (Reynolds, 1989). XRD analysis of samples at intermediate depths shows that the increase in smectite content is gradual with no abrupt changes or interruptions.

This trend of increasing smectite abundance at the top of the Ione section occurs in other Ione deposits both within and outside the local Ione area. For example, smectite with similar XRD peak characteristics and particle size distribution appears at the top of the Ione sandstone section exposed at Jones Butte. The clay deposits in the Gladding McBean mining pits at Lincoln (Figure 1) show a similar increase in smectite near the top of the section. In the Lincoln clay deposits, XRD analysis shows that the "Lincoln #7" clay bed contains no smectite while the overlying "Lincoln #6" clay bed at the top of the section contains about 10% smectite with an XRD pattern virtually identical to the "B3" clay in the Bacon Pit (Figure 17c). Again, smectite occurring in the mudstones at Lincoln possesses the same characteristics as that occurring in the Bacon Pit mudstones. The occurrence of this peculiar form of smectite in Ione sediments appears to be a regional phenomenon.

The character of smectite XRD patterns indicates that the mineral occurs in thick, well ordered crystal packets (Wood, 1994). This character is atypical of soil-derived smectites, which are typically concentrated in the finest clay fraction and yield broad, relatively low intensity XRD peaks. Apparently, the size distribution and

XRD character of smectite in the upper Ione is related to alteration of detrital mica (Wood, 1994). Wood found that smectitized mica is abundant in proximal upper Ione sediments. This form of smectite exhibits sharp diffraction peaks in XRD patterns similar to those of smectite in the Bacon Pit mudstones. In addition, smectitized mica would probably mimic the particle size distribution of mica (i.e., more abundant in coarser size fractions).

The clay deposits in the Bacon Pit probably represent continuous deposition over a period of several thousand years. The upward increase of smectite in the clay beds could reflect the beginning of the transition from kaolinite to smectite as the dominant alteration product of mica in regional soils in response to the climatic tempering that began at the end of the early Eocene. If so, the mineralogical record in the clay deposits of the Bacon Pit suggests that this climatic change may have occurred over a span of perhaps 10,000 years or less—nearly instantaneous with respect to geologic time.

XRD analysis also shows that a trace amount of ordered illite/smectite mixed-layered clay is a component of some of the Ione mudstones in the Bacon Pit (Figure 17c) and some of the sandstones overlying the Edwin Clay at Jones Butte. The trace of I/S clay is probably of detrital origin derived from the fluvial scouring of weathered argillaceous rocks within the metamorphic belts to the east of Ione.

**Micromorphology.** Petrographic analysis of sandstones from an east to west trending transect from Apricum Hill to Jones Butte shows that the modal grain size of quartz sand gradually decreases towards the west (Figure 18). Based on the grain size distribution of quartz grains, these sandstones are moderately well to well sorted (Photo 3, Appendix B). The observed grain size decrease reflects the waning hydrodynamic flow regime of Ione streams as they flowed further into the Ione basin and gradually lost kinetic energy (Wood, 1994).

The hydrodynamic flow regime similarly controlled the modal grain size of detrital kaolinite clasts transported as bedload sediment. In sandstones exposed at Apricum Hill, quartz and kaolinite aggregates are concentrated in the lower medium and lower coarse grain sizes, respectively (Figure 18). A difference of approximately 1.0 $\phi$ exists between the modal grain size of these two constituents. In well sorted sandstones from exposures at the Wallens pit, quartz and detrital clay clasts have a slightly smaller modal grain size than those at Apricum Hill. In spite of this grain size decrease, a 1.0 $\phi$ separation still exists between the clast size of quartz and kaolinite aggregates. The same relationship holds for well sorted sandstones from the Old Sand Plant, Owens-Illinois sand pit, and the very fined-grained sandstones at Jones Butte. The consistency of this grain size separation in well sorted sandstones demonstrates the control of density in determining the modal grain size of hydrodynamically equivalent quartz and clay aggregates (Photo 3, Appendix B). When these hydrodynamically equivalent clasts of differing density were deposited, the larger clay clasts formed clay-filled “gaps” in the sandstone fabric (Photos 3 & 4, Appendix B).

## Intra-Ione Paleosols

Paleosols are sporadically developed in some beds of lower Ione sandstones in the Ione area. One such paleosol is developed on Ione sandstone at Jones Butte. The prominent red iron oxide horizon that identifies these paleosols suggests that significant weathering of the sandstone substrate occurred. However, such discoloration can be produced by as little as a few percent of iron oxide cement (Schwertmann and Taylor, 1989). Thus, the appearance of these horizons in outcrop is a poor indicator of the severity of weathering. In the case of the paleosol in Ione sandstones at Jones Butte, the iron oxide cement occurs at a boundary between permeable coarse-grained sandstones and underlying relatively impermeable very fine-grained clayey sediments. The iron oxide horizon appears to have developed due to a fluctuating water table at an impermeable boundary.

Illuvial clay coatings (clay cutans) are a prominent feature apparent in thin section in the coarse-grained sandstone above the red horizon at Jones Butte. The apparent source of the illuviated clay is the destruction of detrital clay clasts in the sandstone (Wood, 1994). The presence of clay coatings is atypical of Oxisols (Stoop, 1983) and suggests that the intra-Ione weathering profile at this location developed under less severe climatic conditions than the underlying Jones Butte Oxisol. Alternatively, the duration of weathering may have been cut short by renewed deposition of younger Ione sediments. No authigenic kaolinite characterized by vermicular morphologies occurs in this Ione paleosol.

Another exhumed intra-Ione paleosol at Apricum Hill (Figure 13) was classified as an

Oxisol by Singer and Nkedi-Kizza (1980). The paleosol developed within medium-grained lower Ione sandstones and has an iron oxide cemented zone (oxic horizon) at the top of the exhumed profile. The exhumed soil meets the chemical, morphological, and mineralogical requirements of the Oxisol soil order. However, micromorphological properties do not suggest severe *in situ* weathering (Photo 8, Appendix B). Rather than developing the features in response to prolonged weathering, the oxic chemistry and mineralogy were inherited from the kaolinitic lower Ione sandstone substrate (Figure 14, Wood, 1994). In essence, these soils are recycled Oxisols.

Not all of the iron in reddened weathering horizons stems from the dissolution of iron-bearing minerals. Oxidation of iron chelated in organo-siliceous cements in detrital clay clasts in Ione sandstones may also be an important source of reddened horizons (Schwertmann and Taylor, 1989). This process apparently operates during the earliest stages of weathering in Ione sandstones before other chemical weathering processes such as the dissolution or oxidation of amphibole grains occur. Examples of the rapidity of such organo-iron oxidation are seen in recent road cuts along Hwy. 124 (Figure 13). The lower Ione sandstone beds that have been exposed to subaerial weathering for several decades in the face of the roadcut were oxidized and exhibit yellow-brown discoloration (Photo 7, Appendix B). The distribution of goethite cement in the clay aggregates appears to follow the distribution of siliceous cement in the fabric of clay clasts in unaltered Ione sandstones (Photo 5, Appendix B). Sandstones a few inches beneath the face of the outcrop remain unoxidized and appear white.

The fact the organic material remains preserved in Ione sediments such as in mudstones and lignite beds throughout the lower Ione section shows that the sediments buried in the Ione Basin have remained under reducing conditions since accumulation. This implies that either the groundwater table on the Ione flood plain was high during deposition or that sediment burial in the flood plain was relatively rapid—or both. The occurrence of local paleosols in lower Ione sandstones indicates that there were periods of non-deposition when Ione sediments were subaerially exposed for a length of time sufficient for soil profiles to develop. These non-depositional periods could have been caused by channel migration or minor base level fluctuations. However, petrographic evidence indicates that the these periods of surface weathering were too brief to allow the development of deep weathering profiles and the formation of authigenic clay. The bulk of lower Ione sandstones and mudstones escaped the weathering effects of the early Eocene tropical climate and remain unaltered.

## Sandstone Classification

The presence of detrital pedogenic kaolinite clasts in Ione sandstones has important implications for the classification of these rocks. Since few examples of pedogenically influenced sandstones occur in the literature, the classification of such sandstones has not been adequately addressed. The argillaceous Ione sandstones might be classified as "quartz wackes" (Williams *et al.*, 1954; Dott, 1964) since clay constitutes >10% by volume of Ione sediments. However, since kaolinite in Ione sandstones was deposited as coarse clasts of pedogenic clay, it is technically not matrix clay as typically identified in sandstones. Therefore, Ione sandstones should be classified using a scheme that recognizes the clay clasts as framework grain constituents. Customarily, altered detrital argillaceous lithic clasts are grouped as "unidentified lithic fragments"—a component of "unstable rock fragments" (URF's) in the Folk (1974) sandstone classification triangle. In that classification scheme, sandstones with a large amount of URF's are classified as "litharenites". Excluding argillaceous material derived from hydrothermal sources and recycled mudstone fragments, chemically altered argillaceous clasts in clastic fluvial sediments are ultimately soil-derived. Therefore, the clay clasts in Ione sediments should be recognized on the basis of their pedogenic origin.

Various descriptive terminologies have been proposed to distinguish pedogenic clasts in sandstones. Johnsson (1990) used the term "alterites" and "saprosands" (saprolite origin) for various types of highly weathered argillaceous soil clasts in modern tropical sediments. Retallack (1983) applied the term "pedolith" to a sedimentary deposit or rock comprised largely of soil detritus. Rust and Nanson (1989) referred to the term "pedoliths" as describing the individual sand-sized pedogenic clay clasts in sediments. Since kaolinite clasts in Ione Fm. sediments can be attributed to altered lithic material eroded from soils, the term "pedolith" appears to be a useful term to apply to pedogenic clay aggregates and also one that fits nicely into the Folk (1974) classification scheme. This term also encompasses the lateritic ferrugenous class of pedogenic materials.

As pedoliths constitute the majority of lithic materials in Ione sandstones, then "pedoliths" should form the lower right component of the Folk sandstone composition triangle (Figure 19). In this classification scheme, distal lower Ione sandstones in the Ione area plot in the "pedarenite" category. "Pedarenite" is a term that succinctly describes sandstones with a significant component of detrital pedogenic material and fits well with current sandstone classification convention.

## TECTONIC SETTING OF THE IONE FM.

Prior to the Ione depositional period the early Eocene was a time of relative tectonic quiescence in the region of the ancestral Sierras (Bateman and Wahrhaftig, 1966). The development of thick Oxisols and related tropical soils throughout the ancestral Sierras during the early Eocene (and perhaps earlier) provides evidence for this period of tectonic quiescence (Soil Survey Staff, 1975; Buol *et al.*, 1980).

The Ione depositional period was initiated by a significant lowering of the base level that scoured the underlying lateritic landscape and deposited coarse sediment in V-shaped channels and broad troughs (Figure 3; MacGinitie, 1941; Allen 1929; Pask and Turner, 1952). MacGinitie suggested that the drop of the base level was tectonically controlled; however, more recent studies conclude that Sierran tectonic uplift began after Ione deposition (Bateman and Wahrhaftig, 1966). Eustatic processes may have initiated the Ione depositional cycle, with base level changing in response to one of a number of early Eocene eustatic sea level lowstand events (Haq *et al.*, 1987).

The presence of the pre- and intra-Ione paleosols implies that depositional processes were cyclic, with long intervening periods of non-deposition and soil development. These pedogenic episodes may correlate with periods of channel incision related to one of the significant eustatic sea level lowstand events at 58 or 55 Ma identified by Haq *et al.* (1987). Cherven (pers. comm., 1995) agrees that the downcutting event in continental areas probably occurred in response to one of these events simultaneously with significant submarine canyon cutting (i.e., Martinez and Meganos Submarine Canyons) in the adjacent Sacramento Basin to the west.

Chapman and Bishop (1975) used geophysical data to show that at the beginning of lower Ione deposition, the Ione Basin was a north-south oriented elongate trough with a major drainage outlet to the south (Figure 21a). They reported that the configuration of the basin was apparently controlled by a combination of the trend of the less resistant north-south argillaceous metamorphic belt (Salt Springs Slate) and the more resistant greenstone ridge on the west and Sierran granitics on the east.

As sea level later rose during the early Eocene, deposition of lower Ione sediments ensued. Gradually, the incised channels were back-filled—first in distal areas and later in proximal areas (Figures 20 and 21b). MacGinitie (1941) reported that a significant change in the mineralogy of lower Ione sediments occurred when Ione streams in proximal areas crested the margins of the incised channels and began to cut laterally. He believed that bench sediments on the wide flood plains in proximal areas correlate with the distal lower Ione sediments exposed in the Ione area. During this later phase of the "aggradation stage" the greatest erosion of lateritic soils occurred by laterally migrating Ione streams (Figure 20). Weathering of sediments temporarily stored in flood plains and abandoned channels would have promoted the compositional maturing of Ione deposits. Thus, the lower Ione sediments in distal areas at this later stage of deposition not only contain abundant pedogenic kaolinite but also possess very high quartz to feldspar ratios with only a trace of weatherable minerals.

It is not known exactly what length of time passed before upper Ione deposition ensued; however, Pask and Turner (1952) believed that upper Ione sediments were probably deposited before the end of the middle Eocene. Both MacGinitie (1941) and Pask and Turner (1952) reported significant incision of lower Ione sediments by upper Ione channels suggesting another downcutting event.

## DEPOSITIONAL SETTING OF IONE FM.

There has been much speculation over the years as to the specific environment of deposition of Ione sediments in the Ione area (Allen, 1929; Dickerson, 1916; Pask and Turner, 1952). Surface exposures of Ione sediments in the vicinity of Ione were laid down near the end of the lower Ione depositional period after the Ione Basin had been completely backfilled with sediments. Rodgers' (1986) facies analysis shows that coarse-grained lower Ione sediments in the eastern side of the Ione Basin were largely deposited in braided streams flowing towards the west. An inspection of sandstone outcrops in the walls of the Old Sand Plant and Wallens pits (Figure 13) reveals that in addition to thin-bedded braided fluvial deposits, Ione sands fill low sinuosity channels with channel depths of up to 2 m or more. In some areas, braided and low sinuosity channel deposits are stacked.

The close association of low sinuosity channel and braided stream deposits could have been produced by fluctuations of water flow under the tropical climatic regime envisioned for the ancestral Sierras in the Early Tertiary. Wolfe (1978) and MacGinitie (1941) postulated winter dry periods in their climatic models. During drier periods with reduced water flow, streams may have been confined to low sinuosity anastomosing channels. Cohesive clayey flood plain sediments, such as those on the Ione flood plain, can favor the development of stable anastomosing channels (Cant, 1982). In contrast, during periods of high water flow or flooding episodes, the streams were likely to have overflowed the established channel banks and flowed out over the low gradient delta plain as braided streams. Such a depositional setting could explain the contrasting coarse clastic facies occurring in the eastern part of the Ione Basin.

Lower Ione sediments in the western side of the Ione Basin near Jones Butte and the Bacon Pit mining areas (and beyond) have a different character than their eastern basin counterparts. Broad areas dominated by Ione mudstones, such as the deposits in the Bacon Pit and far to the northwest on Van Vleck Ranch properties, are devoid of coarse clastic sediments. No disconformable surfaces with coarser grained lag deposits can be identified in the 10+ m Bacon Pit mudstone section (Dave Jenkins–pers. com., 1993). This suggests that fine-grained sediment deposition in these areas was slow but continuous with time. Major fluvial channels transporting coarse clastic sediments were apparently restricted from these broad areas. The occurrence of lignite beds associated with some of these fine-grained clay deposits such as in the Edwin clay section at Jones Butte and the clay deposits both at Lot 232 and south of Buena Vista (Figure 13) also indicates that these sites of fine-grained sediment deposition were stable for a sufficiently long period of time for the development of thick peat deposits.

Both the particular aspects of the local paleogeography and the style of Ione fluvial deposition probably had an influence on the distribution of Ione sediments in the western Ione Basin. First, during the latter part of lower Ione deposition, Ione streams were flowing across the Ione basin toward the west and passed though gaps in the greenstone ridge outliers (Figure 21b; Rodgers, 1986). These gaps probably had an important control over the upstream location of major fluvial channels. As a consequence of the confinement of the Ione stream channels though these gaps, their courses across the Ione Basin from the east were probably well constrained. Therefore, only during times of high water flow or flood periods would the interdistributary areas between the major Ione fluvial channels have received significant influxes of sediments in the form of overbank deposits. These overbank sediments would have been dominated by fine-grained clay and silt. In addition, the upstream or eastern side of the greenstone outliers between the channels would have been sites of restricted flow and ponding. Such ponded areas would have favored the development of freshwater swamps and the accumulation of peat deposits.

Second, the lignitic mudstone deposits dominant in the western areas of the Ione Basin are characteristic flood plain facies of anastomosing river systems. Semi-permanent islands are a feature of anastomosing systems that cause the river courses to divide and later rejoin downstream (Cant, 1982). Cant suggests that these islands are actually "alluvial islands" comprised of well developed flood plain and swampy areas that extend away from the river channels. While the anastomosing river channels can carry coarse clastic sediments, the alluvial islands and flood plain areas are typically sites of fine-grained clay and peat deposition. In this depositional setting, fine-grained sediments wash over the channel banks into the interior of the alluvial islands in high water or flood periods. Washover sediments comprised of silty sands and sandy silts accumulate adjacent to the channels with only silty clay material reaching the depocenter of the alluvial islands. The alluvial islands cover much larger areas than the channels. Consequently, fine-grained peaty silts and clays are the dominant facies of anastomosing rivers systems.

The distribution of sedimentary facies in the Bacon Pit area appears to be consistent with an anastomosing river system model. Coarse-grained channels sands visible in outcrops a few hundred meters north of the Bacon Pit clay deposits could represent the channel deposits of an anastomosing river system. Well data show that the Bacon Pit mudstones become sandy to the north in the direction of these coarse-grained channel deposits (Dave Jenkins–pers. comm., 1995).

Brackish or marginal marine conditions were postulated for areas of fine-grained clay and peat accumulation in the western Ione Basin based on the occurrence of pyrite in the lignite beds (Rodgers, 1986). However, results of organic geochemical analyses of local lignite and associated mudstones contradict the notion of a marginal marine environment (Stout, this volume). Some of the organic-rich mudstones that occur in the western Ione Basin are actually lignitic mudstones. The pyritic sulfur content of 0.73 wt% in lignitic mudstone from Lot 232 is extremely low compared to the >20 wt% in lignitic mudstone from the Domengine section near Coalinga which formed under the influence of marine water. Since marine water is enriched in sulfate, this low pyritic sulfur value in the Ione mudstone indicates a predominantly freshwater depositional environment. The same argument applies to the lignite deposits themselves (i.e., low sulfur and non-marine biomarkers; see Stout, this volume). Some of the pyritic sulfur in lignite from the Buena Vista locality is of secondary origin, occurring along fractures in the lignite that developed after coalification.

The relatively high mineral content of the Ione lignite (30-40%, dry) indicates that the swamps were occasionally inundated with floodwaters carrying clastic debris. However, inspection of the lignites reveals an absence of coarse-grained clastic detritus. Instead, clay is the dominant inorganic material present. The fact that the swamps persisted to form discrete lignite beds (and not only organic-rich mudstones) indicates that flooding was infrequent. In addition, the great thickness of peat that was required to form the lignite beds that occur locally throughout the Ione Basin is evidence that the freshwater swamps were not only stable and long-lived, but were also isolated from coarse clastic detritus for a period of time on the order of several thousand years. These conditions are consistent with either of the depositional models discussed earlier. The isolation of freshwater swamps on Ione flood plains from the influence of the major river channels facilitated thick accumulations of peat in relatively stable low-lying protected areas either behind the greenstone barriers between the river systems (Figure 21b) or within "alluvial islands" in an anastomosing river system—or both. Further, geochemical data show that the freshwater swamps were beyond the tidal range of marine waters indicating that the shoreline was located somewhere to the west of the greenstone ridge outliers.

## ENGINEERING APPLICATIONS

Ione kaolinitic mudstone material has been used for engineered clay liner material in recent years. One reason for this is purely economic—Ione kaolinite is locally abundant in the Sacramento area, whereas, bentonite material must be imported from further afield. Ione kaolinite appears to perform exceedingly well in this application. While bentonite clay (smectite) achieves the standard permeability of $10^{-7}$ cm/sec required for most engineering applications, Ione kaolinite clay routinely achieves permeabilities of $10^{-8}$ cm/sec and has tested as low as $10^{-9}$ cm/sec (Dave Jenkins, pers. comm.—1995; McDonnell, 1995).

While bentonite and kaolinite clay lining materials are both effective as permeability barriers, their mechanisms of retarding fluid migration are not the same, primarily because of fundamentally different mineral structures. Smectite (montmorillonite)—the clay mineral comprising bentonite—possesses a layered structure with an interlayer site for exchangeable cations. The well-known swelling property of smectite clay is produced by water entering the interlayer site and causing an expansion of the clay layers. The swelling potential of smectite is dependent on the specific exchangeable cations that occupy the interlayer site. For example, sodium cations cause smectite to swell nearly to its full potential. Sodium is the dominant exchangeable cation in Wyoming bentonite. Therefore, when Na-bentonite is properly hydrated, the clay particles swell until all the intergranular porosity is occluded. The expanded clay particles provide a physical barrier to fluid migration. In contrast, calcium cations in the smectite interlayer cause the clay structure to collapse and the clay shrinks or flocculates. Smectite clay also serves as a chemical barrier to contaminant migration because the smectite interlayer attracts and binds both hazardous cations and undesirable organic molecules that may be contained in migrating waters.

Kaolinite does not contain an exchangeable cation interlayer and, therefore, it is non-swelling when in contact with water. Kaolinite particles are planar pseudohexagonal plates. The principle mechanism of kaolinite in inhibiting fluid migration is principally physical. Compaction of kaolinite clay causes the close packing of kaolinite platelets. This results in significant reduction of porosity and permeability.

Bentonite has come to be regarded as a "permanent" clay barrier. However, the longevity of bentonite barrier performance is really unknown because of the lack of long-term performance data. The performance of bentonite clay barriers depends on the integrity of the exchangeable cation interlayer of smectite. Consequently, there is great potential for barrier failure if the smectite interlayer is contaminated with foreign cations. The occurrence of such barrier failures is now being reported in the literature. For example, Dobras and Elzea (1993) reported the failure of a geosynthetic clay liner composed of bentonite because of the introduction of Ca and Mg ions from the dolomitic cover material. The cost and feasibility of successful *in situ* repair of such barrier failures will be dependent on site specifics such as accessibility to the barrier and the location of the barrier material (i.e., does it lie above or below a zone of contaminated fill or liquid material?).

Such potential problems because of chemical contamination are not a problem with kaolinite barriers. The long-term performance of kaolinite barriers will not be appreciably affected by the cation content of solutes coming in contact with the surface of the barrier.

The occurrence of coarsely crystalline smectite in the upper layers of Ione clay beds both in Lincoln and at Ione (Bacon Pit) apparently has an important effect on the properties of kaolinite used for engineered clay liner applications. NARCO prefers to provide their "M21" clay material containing about 25–30% smectite to clients for clay barrier uses. They believe that the larger particle distribution of that particular material has better compaction properties which, in turn, results in lower permeability (Dave Jenkins, pers. comm.—1995). For example, the M21 clay material attains lab permeabilities of $10^{-8}$ to $10^{-9}$ cm/sec (Figure 17) verses $10^{-7}$ to $10^{-8}$ cm/sec for B6 material containing little or no smectite (Figure 16). It is possible that the smectite in the M21 clay affects the plasticity, compaction characteristics, and permeability performance of the clay.

In the past, Gladding McBean has provided clients with "Lincoln 9" clay material for clay liner uses (McDonnell, 1995). This material contains no smectite and attains permeabilities in the range of 3 to $4 \times 10^{-8}$. Another Gladding McBean clay material currently sold for liner applications also falls into this range (McDonnell, 1995). Its mineralogy has not been determined.

The use of silty or sandy Ione clay material for clay liners apparently has no appreciable affect on barrier performance. For example, the predominant clay sediments available for on-site use at the Buena Vista Landfill are clayey medium-grained sandstones with about 50% kaolinite similar to that shown in Photo 3. When compacted, this material apparently performs to required specifications. Similar compacted kaolinitic sandstones perform as effective permeability barriers in nature. Well compacted sandstones with similar kaolinitic compositions occurring in the Gatchell Fm. (Eocene) serve as cap rocks for petroleum reservoirs in several oil fields in the Coalinga area (Wood, 1995).

McDonnell (1995) reported that on-site Ione clay material used for projects in the Ione area was found to be dispersive. Lime was applied to reduce the dispersion potential of clay used in impoundment applications. The dispersive property of some clays in the Ione area could have been produced by smectite. If so, the application of the lime could have a deleterious affect on the long-term performance of the clay barriers. Currently, there is a general lack of knowledge on the part of both suppliers and users of Ione kaolinite as to the mineralogy of products being sold and the affects of variable mineralogy on performance characteristics. A greater knowledge of the properties of Ione clays used for engineering applications may lead to the characterization of the "ideal" Ione clay product that combines the best properties of kaolinite and smectite.

## CONCLUSIONS

Early Eocene deposits in the Ione area, California, developed during a period of relative tectonic quiescence and prolonged tropical weathering. Thick lateritic paleosols mantled a landscape of general low relief and provided a source of compositionally mature sand during episodes of eustatically-driven erosion. Stabilized pedogenic kaolinitic clay clasts were a major component of Ione river bed load and were deposited in association with conglomeratic channel fill and finer-grained, quartzose braided stream sands. The macro- and microscopic properties of these kaolinitic clasts clearly distinguish their pedogenic origin and suggest that Ione sandstones should be classified as pedarenites using a Folkian ternary classification scheme. The amount of post depositional diagenetic kaolinite in Ione sandstones is insignificant, reflecting the provenance-controlled absence of feldspar in these rocks.

Upper Ione deposits differ mineralogically from the kaolinite-dominated lower Ione sediments, containing more feldspar and a clay assemblage with significant amounts of smectite. Much of this smectite evidently developed by pseudomorphous replacement of detrital mica and occurs as macroscopic smectite flakes. The change in Ione mineralogy during later stages of deposition probably reflects changing global climatic conditions. The climatic and tectonic regime of Ione deposition was probably typical of large areas of coastal western North America and suggests that sediments rich in detrital kaolinite may occur elsewhere in the early Tertiary geologic section.

Post-depositional weathering of Ione sediments is indicated by the presence of paleosols observed in surface exposures of proximal and distal Ione deposits. However, the interpreted severity of weathering associated with these paleosols has been grossly overestimated. Petrographic evidence indicates that the oxidation of iron chelated with organo-siliceous cements in the detrital clay clasts is a major cause of the iron oxide coloration of these paleosols. Congruent dissolution of weatherable minerals occurred in the upper horizons of the paleosols; however, the weathering regime was not of the severity nor of sufficient duration to form authigenic kaolinite.

Engineering uses of the Ione clays may vary depending upon smectite content and particle size distribution. Lower Ione sands yield refractory-grade kaolinite and pure quartz sand. Upper Ione deposits with smectite/kaolinite mineralogy are an economic source material for construction of landfill liners, offering low permeability and excellent compaction characteristics. Because of the relatively inert character of kaolinitic clays, liners prepared from Ione material are not sensitive to chemically-induced liner degradation. Furthermore, the low cost of these locally-available clays means that thicker liners can be prepared to delay diffusion-related breakthrough that occurs in thin smectite barriers. Mineralogical characterization of Ione clays should be a routine requirement prior to engineering applications.

## REFERENCES

Allen, V. T., 1929, The Ione Formation of California: Bulletin of the Department of Geological Sciences, University of California Publications, v. 18, no. 14, p. 347–448.

Allen, V. T., Fahey, J. J., and Ross, M., 1969, Kaolinite and anauxite in the Ione Formation, California: The American Mineralogist, v. 54, p. 206–211.

Bateman, P. C., and Wahrhaftig, C., 1966, Geology of the Sierra Nevada, *in* Bailey, E. H., ed., Geology of Northern California: California Division of Mines and Geology Bulletin 190, p. 107–169.

Bates, T. F., 1945, Origin of the Edwin Clay: Geological Society of America Bulletin, v. 56, p. 1–38.

Birkeland, P. W., 1984, Soils and Geomorphology: Oxford, Oxford University Press, 372 p.

Brewer, R., and Sleeman, J. R., 1969, The arrangement of constituents in Quaternary soils: Soil Science, v. 107, n. 6, p. 435–441.

Bullock, P., Fedoroff, N., Jongerius, A., Stoops, G., and Tursina, T., 1985, Handbook for soil thin section description: Wolverhampton, U.K., Waine Research Publications, 152 p.

Buol, S. W., Hole, F. D., and McCracken, R. D., 1980, Oxisols: Sesquioxide-rich, highly weathered soils of the intertropical regions, *in* Soil Classification and Genesis: Ames, Iowa, Iowa State University Press, p. 282–289.

Cant, D. J., 1982, Fluvial facies models and their application, *in* Scholle, P. A., and Spearing, D., eds., Sandstone Depositional Environments: Tulsa, American Association of Petroleum Geologists, Memoir 31, p. 115–137.

Carlson, D. W., and Clark, W. B., 1954, Mines and mineral resources of Amador County, California: California Journal of Mines and Geology, v.50, p. 149–285.

Chamley, H., 1989, Clay formation through weathering, *in* Clay Sedimentology: Paris, Springer-Verlag Publishers, p. 21–50.

Chapman, R. H., and Bishop, C. C., 1975, Geophysical investigations in the Ione area, Amador, Sacramento, and Calaveras Counties, California: California Division of Mines and Geology Special Report 117, 27p.

Cherven, V. B., 1983, Stratigraphy, facies, and depositional provinces of the middle Eocene

Domengine Formation, southern Sacramento Basin, *in* V. B. Cherven and Graham, S. A., eds., Geology and sedimentology of the southwest Sacramento Basin and East Bay Hills: Pacific Section S.E.P.M. Field Trip Guide, p. 59–79.

Clark, L. D., 1964, Stratigraphy and structure of part of the Western Sierra Nevada Metamorphic Belt: United States Geological Survey Professional Paper 410, 70 p.

Dickerson, R. E., 1916, Stratigraphy and fauna of the Tejon Eocene of California: Bulletin of the Department of Geological Sciences, University of California Publications, v. 9, p. 387–417.

Dickinson, W. R., 1970, Interpreting detrital modes of graywacke and arkose: Journal of Sedimentary Petrology, v. 40, no. 2, p. 695–707.

Dobras, T. N., and Elzea, J. M., 1993, In situ soda ash treatment for contaminated geosynthetic clay liners: 1993 Geosynthetics Industry Conference, Vancouver, Canada.

Dott, R. H., 1964, Wacke, graywacke, and matrix—what approach to immature sandstone classification?: Journal of Sedimentary Petrology, v. 34, p. 625–632.

Flach, K. W., Nettleton, W. D., Gile, L. H., and Cady, J. G., 1969, Pedocementation: induration by silica, carbonates, and sesquioxides in the Quaternary: Soil Science, v. 107, n. 6, p. 442–453.

Folk, R. L., 1974, Petrology of Sedimentary Rocks: Austin, Texas, Hemphill Publishing Co., 182 p.

Frakes, L. A., Francis, J. E., and Syktus, J. I., 1992, Climate Modes of the Phanerozoic: Cambridge, England, Cambridge University Press, 274 p.

Franzinelli, E., and Potter, P. E., 1983, Petrology, chemistry, and texture of modern river sands, Amazon River System: Journal of Geology, v. 91, p. 23–39.

Gillam, M. L., 1974, Contact relations of the Ione and Valley Springs Formations in the Buena Vista area, Amador County, California: M.S. thesis, Stanford Univ., California, 180 p.

Glasmann, J. R., Wood, J. L., and Southard, R., 1989, Clays of the Ione Formation, Sierran Foothills, Central California: Field Trip Guide, 1989 Clay Minerals Society Annual Meeting, Sacramento, CA, 26 p.

Goldish, S. S., 1938, A study in rock-weathering: Journal of Geology, v. 46, p. 17–58.

Haq, B. U., Hardenbol, J., and Vail, P. R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156–1167.

Johnsson, M. J., 1990, Overlooked sedimentary particles from tropical weathering environments: Geology, v. 18, p. 107–110.

Johnsson, M. J., and Meade, R. H., 1990, Chemical weathering of fluvial sediments during alluvial storage: The Macuapanim Island point bar, Solimoes River, Brazil: Journal of Sedimentary Petrology, v. 60, p. 827–842.

Johnsson, M. J., Stallard, R. F., and Lundberg, N., 1991, Controls on the composition of fluvial sands from a tropical weathering environment: Sands of the Orinoco River drainage basin, Venezuela and Colombia: Geological Society of America Bulletin, v. 103, p. 1622–1647.

Keller, W. D., 1982, Anauxite viewed by scanning electron microscopy: Clays and Clay Minerals, v. 30, no. 5, p. 391–393.

Langston, R. B., and Pask, J. A., 1969, The nature of anauxite: Clays and Clay Minerals, v. 16, p. 425–436.

Lindgren, W., 1894, Sacramento Folio: U.S.G.S. Geologic Atlas No. 5.

McDonnell, M., 1995, Engineering characteristics and applications of Ione Formation clay, *in* Glasmann, J. R., and Wood, J. L., eds., Geology and Engineering Properties of the Economic Clay Deposits in the Vicinity of Ione, California: Field Trip Guide, Association of Engineering Geologists, 1995 Annual Meeting, Sacramento, CA.

MacGinitie, H. D., 1941, A middle Eocene flora from the central Sierra Nevada: Washington, D.C., Carnegie Institution of Washington Publication 534, 178 p.

Miller, K., 1991, Middle Eocene to Oligocene stable isotopes, climate, and deep-water history: The terminal Eocene event? [M.S.

thesis]: Palasades, New York, Lamont-Doherty Geological Observatory.

Nilsen, T. H., and Kerr, D. R., 1978, Paleoclimatic and paleogeographic implications of a lower Tertiary laterite (latosol) on the Iceland-Faeroe Ridge, North Atlantic region: Geological Magazine, v. 115, no. 3, p. 153–181.

Oades, J. M., 1989, An introduction to organic matter in mineral soils, *in* Dixon, J. B., and Weed, S. B., eds., Minerals in Soil Environments: Madison, Wisconsin, Soil Science Society of America Book Series, no. 1, p. 89–160.

Parham, W. E., 1970, Clay mineralogy and geology of Minnesota's kaolin clays: Minnesota Geological Survey, Special Publication 10, 142 p.

Pask, J. A., and Turner, M. D., 1952, Geologic and ceramic properties of the Ione Formation, Buena Vista area, Amador County, California: California Division of Mines and Geology Special Report 19, 39 p.

Peterson, G. L., and Abbott, P. L., 1979, Mid-Eocene climatic change, southwestern California and northwestern Baja California: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 26, p. 73–87.

Retallack, G. J., 1983, A paleopedological approach to the interpretation of terrestrial sedimentary rocks: The mid-Tertiary fossil soils of Badlands National Park, South Dakota: Geological Society of America Bulletin, v. 94, p. 823–840.

Rodgers, C. L., 1986, Depositional environments of the Ione Formation, east-central California: M.S. thesis, California State University at Fresno, 114 p.

Rust, B. R., and Nanson, G. C., 1989, Bedload transport of mud as pedogenic aggregates in modern and ancient rivers: Sedimentology, v. 36, p. 291–306.

Schwertmann, U., and Taylor, R. M., 1989, Iron oxides, *in* Dixon, J. B., and Weed, S. B., eds., Minerals in Soil Environments: Madison, Wisconsin, Soil Science Society of America Book Series, no. 1, p. 379–438.

Sigleo, W., and Reinhardt, J., 1988, Paleosols from some Cretaceous environments in the southeastern United States, *in* Reinhardt, J., and Sigleo, W. R., eds., Paleosols and Weathering through geologic time: Principles and applications: Geological Society of America Special Paper 216, p. 123–142.

Singer, A., 1979, The paleoclimatic interpretation of clay minerals in soils and weathering profiles: Earth-Science Reviews, v. 15, p. 303–326.

Singer, M. J., and Nkedi-Kizza, P., 1980, Properties and history of an exhumed Tertiary oxisol in California: Soil Science Society of America Journal, v. 44, p. 587–590.

Singh, B., and Gilkes, R. J., 1993, The recognition of amorphous silica in indurated soil profiles: Clay Minerals, v. 28, p. 461–474.

Soil Survey Staff, 1975, Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys: Soil Conservation Service Agriculture Handbook No. 436.

Stoops, G. 1983, Micromorphology of the oxic horizon, *in* Bullock; P., and Murphy, C. P., eds., Soil Micromorphology, Volume 2: Berkhampstead, Academic Publishers, p. 419–440..

Stout, S. A., 1995, Organic petrology and geochemistry of the Ione Lignite, Amador County, California, *in* Glasmann, J. R., and Wood, J. L., eds., Geology and Engineering Properties of the Economic Clay Deposits in the Vicinity of Ione, California: Field Trip Guide, Association of Engineering Geologists, 1995 Annual Meeting, Sacramento, CA.

Turner, H. W., 1894, Jackson Folio: U.S.G.S. Geologic Atlas No. 11.

Williams, H., Turner, F. J., Gilbert, C. M., 1954, Petrography: San Francisco, Freeman, 406 p.

Wilson, M. D., and Pittman, E. D., 1977, Authigenic clays in sandstones: recognition and influence on reservoir properties and paleoenvironmental analysis: Journal of Sedimentary Petrology, v. 47, p. 3–31.

Wolfe, J. A., 1985, Distribution of major vegetational types during the Tertiary, *in* Sundquist, E. T., and Broecker, W. S., eds., The Carbon Cycle and Atmospheric $CO_2$: Natural Variations Archean to Present: Washington, D.C., American Geophysical Union, p. 357–375.

Wolfe, J. A., 1978, A paleobotanical interpretation of Tertiary climates in the Northern Hemisphere: American Scientist, v. 66, p. 694–703.

Wood, J. L., 1995, The occurrence of kaolinite in the Gatchell Formation and implications for reservoir quality: UNOCAL Energy Resources Division Technical Memorandum #EST AG 94-56M.

Wood, J. L., 1994, A re-evaluation of the origin of kaolinite in the Ione depositional system (Eocene), Sierra Foothills, California—M.S. thesis: Los Angeles, Department of Geological Sciences, California State University at Los Angeles, 211 p.

Yeend, W. E., 1974, Gold bearing gravels of the ancestral Yuba River, Sierra Nevada, California: U. S. Geological Survey Professional Paper 772, 44p.