A RE-EVALUATION OF THE ORIGIN OF KAOLINITE IN THE IONE DEPOSITIONAL SYSTEM (EOCENE), SIERRA FOOTHILLS, CALIFORNIA

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by

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This study also benefited from the ethic of the early gold miners (fortunately now obsolete) whose greed and wanton disregard for the environment led to the development of hydraulic mining techniques, elevating man-made erosion to geologic proportions. As a result, many cubic miles of overburden were removed, nicely exposing several of the sites studied in this project.

ABSTRACT

A Re-evaluation of the Origin of Kaolinite in the Ione Depositional System (Eocene), Sierra Foothills, California

James L. Wood

Kaolinitic sediments in the Ione Formation (early Eocene) were deposited in fluvial, deltaic, and marginal marine environments. Theories differ as to the origin of the kaolinite in Ione Fm. sandstones and mudstones. One holds that the kaolinite is largely detrital from the erosion of widespread thick lateritic soils which developed on the Paleozoic and Mesozoic basement rocks in the foothills of the ancestral Sierras as a result of the long period of globally warm climatic conditions that extended from Late Cretaceous through middle Eocene times. In the opposing view, Ione sediments were initially of arkosic composition and kaolinite was produced by the post-depositional *in situ* chemical weathering of feldspar under the postulated early Eocene tropical climatic conditions. This controversy is resolved through a comprehensive petrographic study of kaolinite in the Ione fluvial system including source rocks, and proximal and distal fluvial deposits.

Lateritic paleosols underlie the Ione fluvial and deltaic deposits over its entire areal extent. These soils are characterized by a mineralogy of kaolinite, iron oxides, and residual quartz. The deeply weathered soils probably meet the criteria to be classified as Oxisols. Differential chemical weathering of precursor minerals produced a great diversity of kaolinite microfabrics and particle sizes in the resulting soil material. Soil processes in the Oxisols produced a fabric characterized by sand-sized clay aggregates stabilized by the inherent nature of the pedogenic kaolinite microfabric. Pedogenic cements including amorphous silica and iron oxides saturate much of the kaolinite fabric of the Oxisols and probably enhance the stability of kaolinite soil aggregates.

Episodes of base level lowering caused significant erosion of the Oxisols mantling the ancestral Sierras in the early Eocene. Consequently, tremendous volumes of kaolinitic detritus were shed into the overlying Ione fluvial system. Kaolinite was transported as bedload sediment in the Ione fluvial system in the form of stabilized sand-sized pedogenic clay aggregates and suspended clay. Following deposition the detrital clay aggregates were deformed by compaction and formed "pseudomatrix" making them difficult to distinguish from authigenic forms of clay. However, detrital pedogenic kaolinite aggregates possess diagnostic micromorphologies which allow them to be distinguished from authigenic pore-filling forms.

Post-depositional weathering of Ione Fm. sediments occurred to varying degrees. The weathering of Ione sediments in alluvial storage on the floodplain in proximal areas in combination with contemporaneous fluvial reworking collectively created a sediment compositional maturing process. This process similarly operates in modern tropical river systems. This weathering mechanism resulted in a quartzose sediment composition in distal area deposits dominated by quartz and detrital forms of kaolinite with only trace amounts of weatherable minerals. The effects of the weathering of distal Ione sediments are minimal because of the rapid burial of sediments on the delta plain. Where weathering of distal sediments is apparent, its affect is local. Evidence indicates that little if any additional kaolinite formed in Ione Fm. sediments exposed in the Ione area as a result of post-depositional weathering.

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PREFACE

A system is defined as "an assemblage or combination of things or parts forming a complex or unitary whole" (Random House). Such is the case of the Eocene Ione depositional system. The unique mineral assemblage characteristic of the Ione Formation formed as the result of the interaction of a number of important processes—tropical climatic conditions; intense chemical weathering; and regional base level fluctuations. Consequently, any attempt at understanding the genesis of the unique Ione sediments requires an examination of all of the individual processes involved in the "system" and their interaction. This thesis is a cursory attempt at this approach.

A large volume of material derived from soils (pedogenic) comprises Ione fluvial sediments. The occurrence and transportability of this soil material in the Ione fluvial system was predetermined by the soil processes that modified the source rocks long before these materials became part of the Ione fluvial detritus. Consequently, to demonstrate the genetic role of soil processes in determining the character of the detritus in the Ione fluvial system, I felt that it was crucial to adequately characterize the nature of the mineral constituents of the precursor soils. Soil scientists will probably find my description of the soils mentioned in this paper inadequate by their standards. In fact, I believe the specific soils discussed in this study are important and merit a comprehensive description on their own. However, the goal here was not to conduct a detailed soil study but merely to demonstrate the interrelationships of the soil constituents and the fluvial detritus. Hopefully, my use of pedological terminology and descriptions to characterize the soil materials will be sufficiently clear for geologists, yet, aren't too oversimplified to be offensive to soils people.

Much work has been conducted on the Ione Formation in the past. What is new in this work is the introduction and use of some analytical tools that weren't available to the early workers. Unfortunately, it is tempting to regard the modern sophisticated electronic instruments that are available to us now, such as the SEM and microprobe, as a panacea of scientific investigation and forget the usefulness and benefits of good old fashioned field observations—the area in which the early workers excelled. Because of their vast field experience, the observational abilities and accomplishments of some of the early workers are unsurpassed today and much of their work and conclusions can still stand up to modern scientific scrutiny. Thus, in order to avoid over-relying on ultramicroscopic techniques to reach conclusions, a pitfall that can lead to the "can't see the forest for the trees" syndrome, I have relied heavily on the extensive field observations of some of the early "masters" such as Victor Allen and Harry MacGinitie. My objective was to mesh the results of this work with those of the previous workers to contribute to a more accurate and up to date view of the "big picture".

I've attempted to bring a number of diverse realms of investigation together to show the importance of soil processes to the transportability and occurrence of argillaceous material in clastic sediments. Of course, I was not able to address all the topics in the detail that is required for a complete understanding. My hope is that this work will pique the interest of the people with the real expertise in these diverse fields of study on which I have audaciously tread so that my initial observations and conclusions can be refined or modified (or thrown out altogether) as the case may be. Ultimately, only a comprehensive interdisciplinary approach—with contributions from diverse fields of study including mineralogy, igneous and metamorphic petrology, pedology, sedimentology, sequence stratigraphy, and organic geochemistry—will lead to a thorough understanding of the interrelated processes that led to the formation of the unique sediments of kaolinitic composition (and of economic importance) preserved throughout the geologic record such as the Ione Formation.

INTRODUCTION

The Ione Formation is an early to middle Eocene (Domengine) sequence of clastic sedimentary rocks which 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 (Fig.1). Ione Fm. deposits are characterized by kaolinitic sandstones and mudstones with interbedded lignite. Ione sediments were deposited at the western margin of an Eocene landscape of low relief now occupied by the Sierra Nevada mountains. Outcrops occurring at the hinge line between the Sierra Nevadas and the San Joaquin Valley include distal fluvial, deltaic, and marginal marine deposits. The Ione sedimentary system also includes proximal fluvial channel deposits located in the Sierras to the east and marine sediments in the subsurface in the Sacramento Basin to the west.

The Ione Formation Defined

Although Lindgren (1894) was the first to use the name Ione as a formation name, it was Turner (1894) who defined the type section near the town of Ione, California. The most extensive study of the Ione Fm. was conducted by Allen (1929). He restricted the Ione Fm. to those sediments with kaolinitic quartzose sands and clays which are characteristic of the Ione Fm. over its entire areal extent. Thus, he excluded an overlying rhyolitic tuff ("clay rock") in his definition of the Ione Fm. that was originally included by Turner (1894). However, Allen noted a significant mineralogical change in upper beds of Ione sandstones in several localities. He reported that these sands and clays contain up to 30% feldspar. Although he didn't break out these feldspathic sediments as a separate member, he proposed that these upper feldspathic Ione sands correlate with the upper proximal gravels mapped by Lindgren (1894), while the lower 150–180 meters (500–600 ft) of kaolinitic quartzose Ione sands are equivalent to Lindgren's quartzose deep gravels. MacGinitie (1941) reported that kaolinitic proximal Ione sediments near Nevada City are overlain by 30 meters (100 ft) of feldspathic, biotitic sands. Based on these mineralogical differences, he reiterated Allen's (1929) suggested correlation of upper and lower Ione members.

Pask and Turner (1952) formally subdivided the Ione Fm. into upper and lower members that recognize the mineralogical differences described by the earlier workers. Their definition of the Ione Fm. at the type section consists of a 125 meter (415 ft) thick lower member of kaolinitic sandstones and mudstones with high quartz to feldspar ratios. Their upper member is a 50 meter (160 ft) section of sandstones and mudstones containing a significantly greater abundance of feldspar, biotite, and chlorite. They reported that the upper member is separated from the lower member by an erosional unconformity in the same stratigraphic position as described by MacGinitie (1941) for proximal Ione deposits. In addition to stratigraphic differences in clast mineralogy, Pask and Turner (1952) also noted significant differences in the matrix clays of the two members based solely on differential thermal analysis (DTA). Their DTA data show that clays in the lower member are characterized by kaolinite with no significant occurrence of other clay mineral species, while upper member sediments are comprised of a more complex clay mineral assemblage (specific clay species not reported).

Geologic Background

Lindgren (1911) initially mapped the continuity of the Early Tertiary (Eocene) auriferous fluvial channel gravels in the Sierra Nevadas with Ione Fm. deposits to the west (Fig. 2). He believed that the Early Tertiary auriferous channels represented fluvial systems that transported Sierran derived sediments to deltas at the margin of an Eocene sea, with the Ione Fm. representing those deltaic deposits. Allen (1929) conducted a comprehensive survey of Ione Fm. exposures and

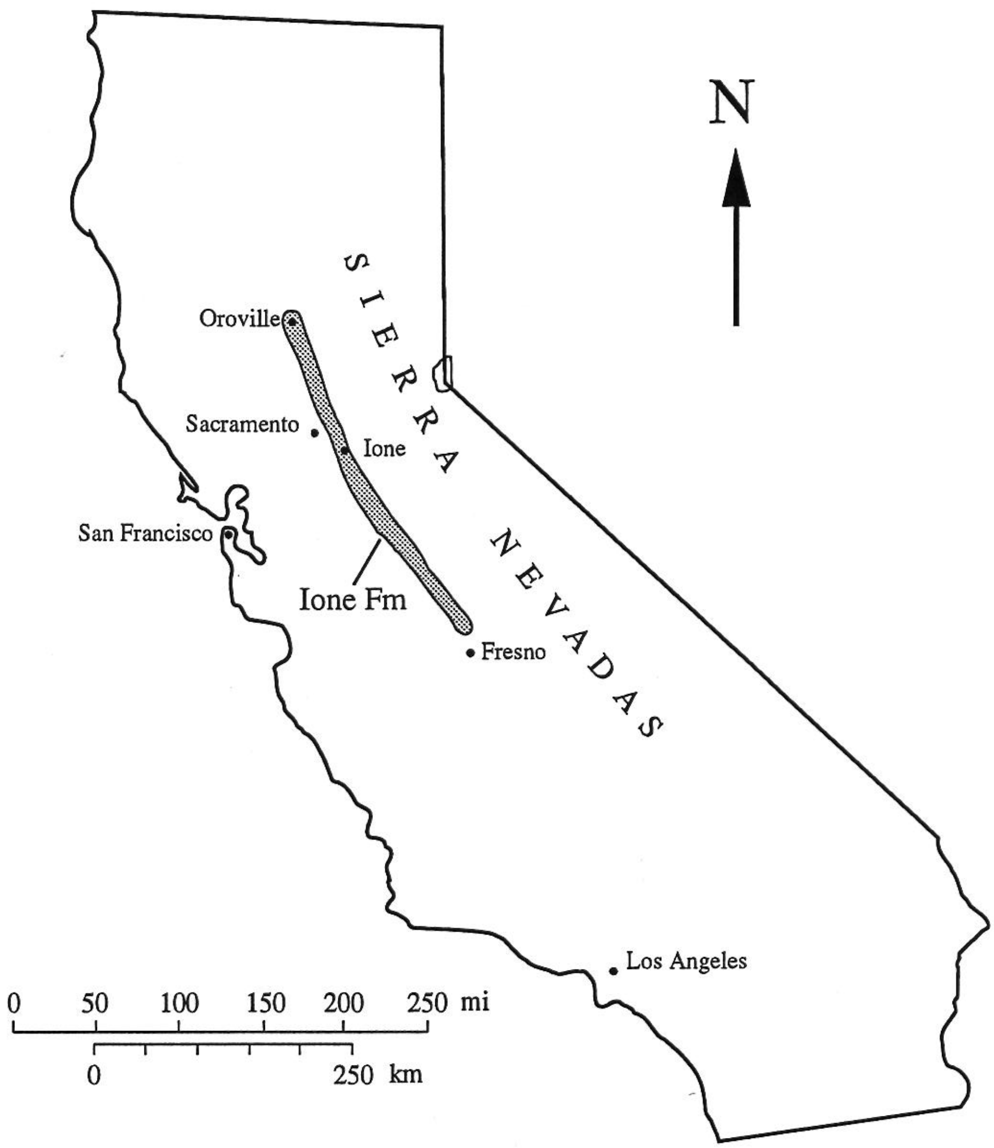


Figure 1
The distribution of the Ione Formation in California.

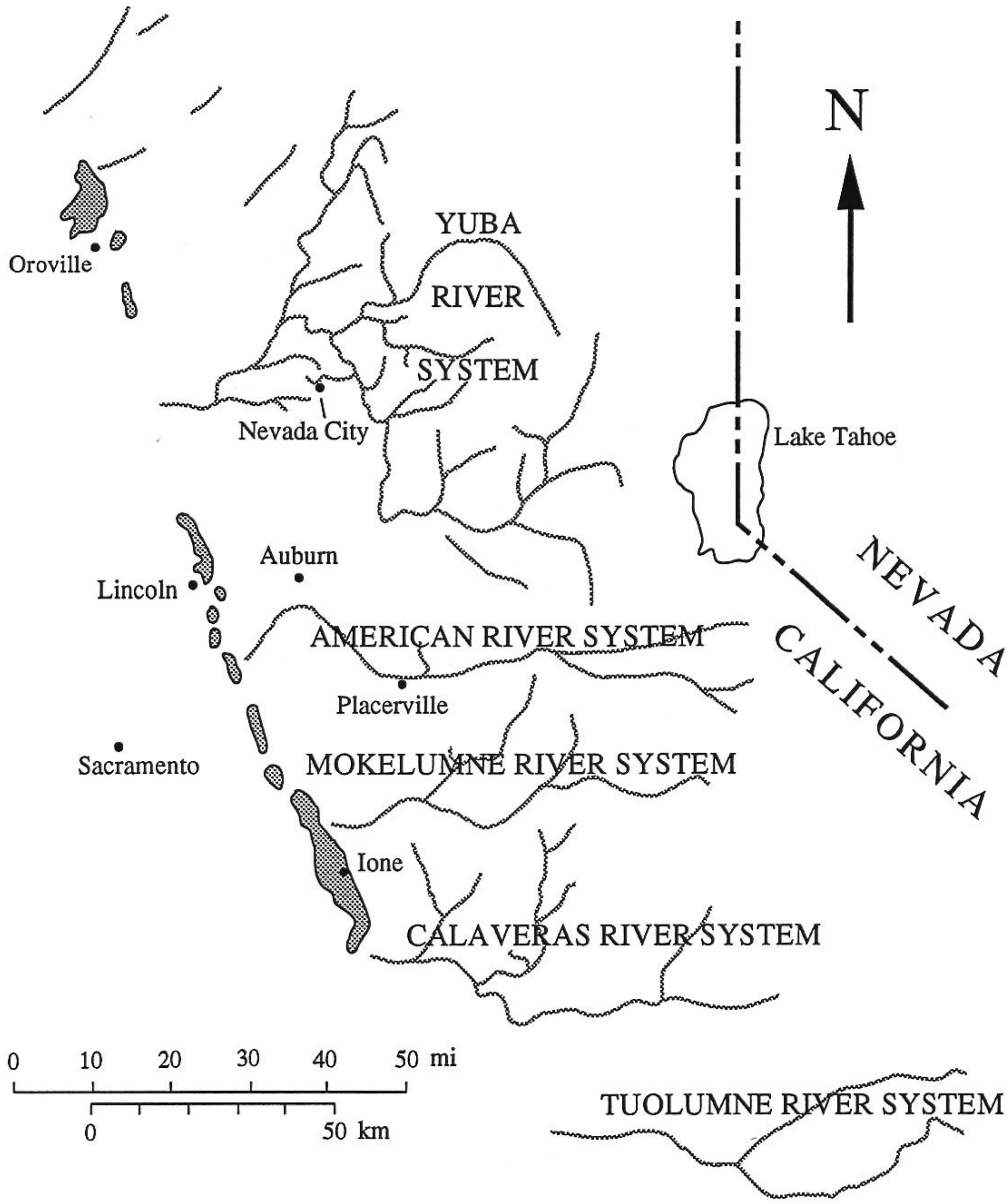


Figure 2
Ione Formation outcrops and
Early Tertiary fluvial channel systems.
(adapted from Clark, 1965; Bateman and Wahrhaftig, 1966)

potential sediment source areas. His work supports Lindgren's (1911) correlation by showing that auriferous channel deposits of the Sierran system merge with distal Ione Fm. deposits. Allen (1929) also showed that the mineral suites in the sediments of both systems are identical. For the same reasons, Allen (1941) proposed that kaolinitic Eocene fluvial sediments in the Coast Ranges and in the subsurface in the Sacramento Basin were derived from a combination of local sources and the long distance transport of Ione sediments from Sierran sources. Durrell (1966) also suggested that the Ione Fm. extends westward into the subsurface and is probably equivalent to the marine Domengine Fm. to the west and south. More recently, Cherven (1983) demonstrated the correlation of terrestrial Ione Fm. sediments with kaolinitic marine Domengine-age units throughout the Sacramento Basin in well logs.

Proximal Ione fluvial channels and the underlying weathered granitic and metamorphic bedrock surfaces were preserved by the deposition of late Eocene through Pliocene rhyolitic and andesitic volcaniclastic deposits which flooded and buried the Eocene river valleys (Lindgren, 1911; Allen, 1929; MacGinitie, 1941; Bateman and Wahrhaftig, 1966; Yeend, 1974). Subsequent regional uplift of the Sierras beginning in Pliocene times (Unruh, 1991) caused the preferential erosion of the surrounding less resistant Paleozoic and Mesozoic igneous and metamorphic basement rocks leaving the Early Tertiary fluvial channels with their resistant volcanic caps as inverted topography (Fig. 3).

Gold miners in the 1850's quickly discovered that the proximal Ione fluvial deposits ("Early Tertiary auriferous gravels") were gold-bearing. The technique of hydraulic mining was perfected on these gold-bearing deposits and led to the erosion of enormous volumes of Ione fluvial sediments. The miners soon realized the highest concentration of gold was found at the interface of the earliest Ione deposits and the underlying weathered bedrock surfaces. Gold caught in the irregularities of the weathered bedrock surface was the ultimate goal of the "hydraulicking" (Jenkins, 1946; Bateman and Wahrhaftig, 1966; Yeend, 1974). Consequently, mining activity exhumed this weathered bedrock surface in the floor of many hydraulic mining pits. Although most of these exhumed bedrock surfaces were later buried by subsequent mining debris and more recent urban development, a few examples of these severely weathered bedrock surfaces remain exposed in some of the abandoned hydraulic mining pits.

Work by Allen (1929), Bates (1945), and Singer and Nkedi-Kizza (1980) contain the only descriptions of extensive soil development associated with the Ione Fm. Of these, only Allen (1929) dealt with potential source materials of Ione sediment. Albeit brief, he described the mineralogy of the severely weathered granodiorite basement rock underlying the Ione fluvial deposits near Nevada City in the Manzanita hydraulic mining pit.

Origin of Kaolinite

Detrital Model

An integral part of Allen's (1929) interpretation of the origin of kaolinite in Ione Fm. sediments was the premise of long distance transport of kaolinitic detritus from Sierran sources. This detrital mechanism for the occurrence of kaolinite in the Ione Fm. was based on his observations of the contact relationship between proximal Ione fluvial channel deposits and the underlying severely weathered bedrock surface.

Where granodioritic bedrock below Ione fluvial deposits was exhumed in hydraulic mining pits near Nevada City (Manzanita site), Allen (1929) reported that the original minerals were so severely altered by intense chemical weathering that feldspar and all other weatherable minerals altered to form a fine-grained kaolinite matrix. He noted that quartz is the only survivor of the original mineral suite. He also reported that biotite pseudomorphically altered to large pearly

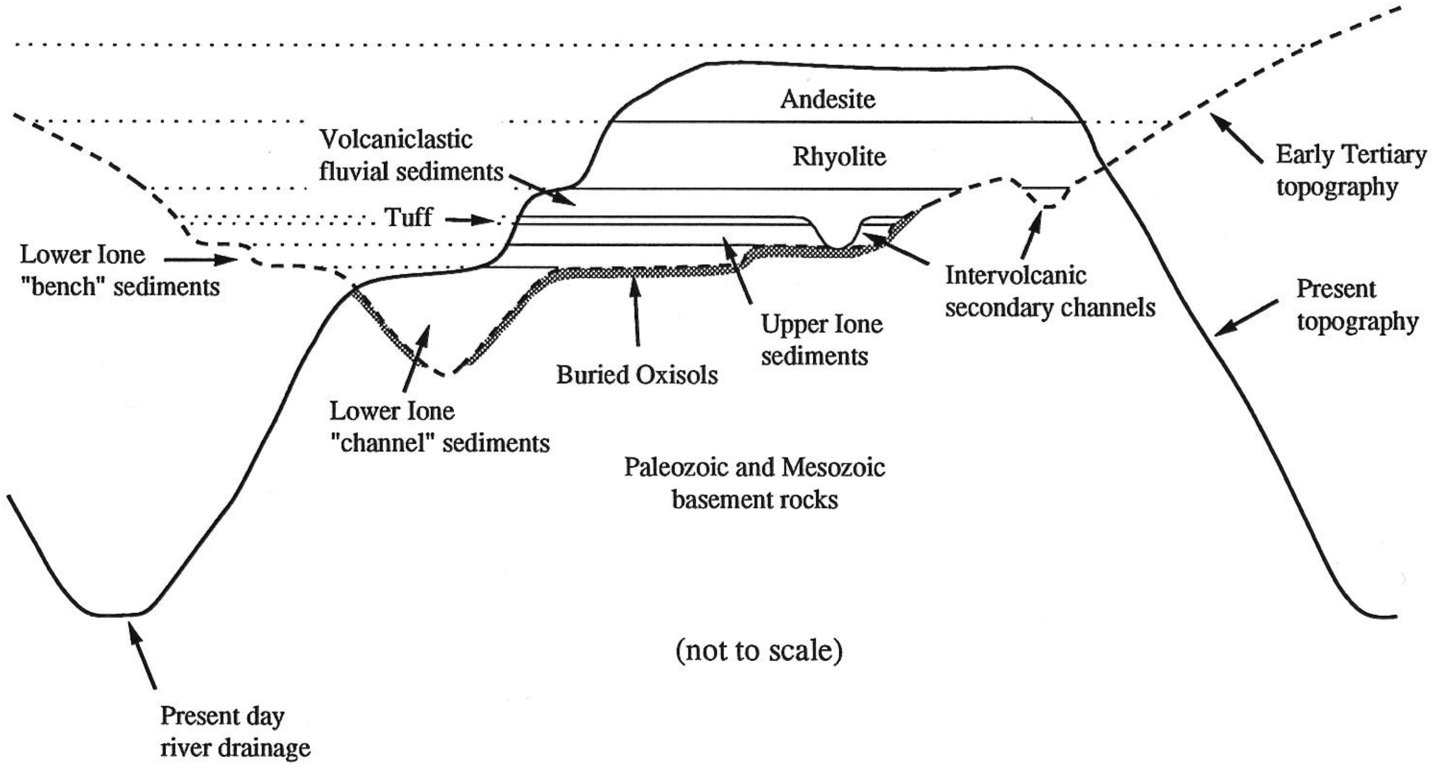


Figure 3

Schematic view of Early Tertiary topography vs. present day inverted topography. The diagram shows the relationship of the buried Oxisols developed on Paleozoic and Mesozoic basement rocks to the Eocene river channels and overlying Tertiary sediments.

flakes of a kaolinite polymorph that he called "anauxite", a term since discredited. He called this severely weathered clay-rich rock that retained the fabric of the parent rock—"lithomarge". The term "saprolite" is now used to describe such material.

Allen concluded that the intense chemical alteration of the Sierran bedrock surfaces that occurred prior to Ione fluvial deposition was the result of regional tropical climatic conditions, as he found lateritic soils preserved below Ione Fm. deposits over its entire areal extent. Pask and Turner (1952) similarly found laterite development on bedrock below the Ione Fm. in drill cores throughout the Ione area.

Allen's (1929) observation that the proximal Ione fluvial deposits contained weathered detritus, including kaolinized mica ("anauxite"), similar to the underlying saprolite, convinced him that widespread erosion of the weathered Sierran granitic and metamorphic bedrock was the major source of detritus transported in the Ione fluvial system. He believed that the transport of weathered Sierran bedrock debris alone accounted for the unique mineral suite of Ione Fm. fluvial deposits which includes little more than quartz, kaolinite, large pearly kaolinized mica flakes ("anauxite"), and resistate heavy minerals. Subsequent work by Bates (1945), and Pask and Turner (1952) supports the basic premise of Allen's (1929) detrital interpretation for the characteristic Ione lithology.

Post-Depositional Authigenic Model

More recent workers (Gillam, 1974; Rodgers, 1986) postulated that Ione sediments were in a large part arkosic at the time of deposition and that considerable kaolinite formed *in situ* through post-depositional chemical weathering of feldspar under the tropical climatic conditions that prevailed during Paleocene through early Eocene times. Their authigenic interpretation is based primarily on petrographic observations of abundant delicate vermicular kaolinite morphologies in the clay matrix of Ione sandstones. Wilson and Pittman (1977), who comprehensively outlined criteria for distinguishing authigenic from detrital clay in sandstones, proposed that the occurrence of delicate crystalline clay morphologies in sandstones would "preclude extended transport", indicating an authigenic origin. Further, they noted that this particular criterion is "very reliable" for clays such as kaolinite. Although experiments have shown that delicate vermicular kaolinite morphologies can be transported short distances (Keller, 1977; Robert Pruett-ECCI, personal communication, 1992), it is difficult to imagine how these delicate crystalline forms could survive the rigors of long distance fluvial transport as "discrete" particles.

Other kaolinitic sedimentary deposits have similarly ambiguous genetic interpretations. For example, conflicting interpretations hypothesized for the origin of Georgia kaolin deposits parallel those for the Ione (Keller, 1978; Patterson and Murray, 1984; Dombrowski, 1990).

Two key petrographic features observed in Ione sandstones conflict with an post-depositional weathering (authigenic) scenario for Ione kaolinite genesis and led to the initiation of this present study. First, leached skeletal grain remnants and moldic pores of dissolved feldspar grains are not apparent in Ione sandstones in the Ione area. These dissolution features are typically observed in sandstones in which significant feldspar dissolution has occurred and compaction of the rock fabric has been minimal. Second, if the large volume of kaolinite and paucity of weatherable minerals occurring in Lower Ione sediments were the result of chemical weathering of the postulated feldspathic detritus, the tropical climatic conditions that led to this characteristic mineral assemblage would have been quite severe. Yet, iron-bearing minerals such as amphibole and biotite, which occur in trace amounts in Ione sandstones, show no signs of weathering and delicate sedimentary structures are unaffected. While these complicating factors do not immediately nullify the post-depositional weathering scenario, they do pose a significant "red flag" for endorsement of that genetic hypothesis.

Study Goals

Recent interpretations promoting a largely post-depositional *in situ* origin for Ione kaolinite (Gillam, 1974; Rodgers, 1986) rely on petrographic observations of Ione Fm. sandstones limited to the Ione area—the distal end of the Ione depositional system. Fundamental to a better understanding of the origin of Ione kaolinite is the need for the characterization of the micromorphology and mode of occurrence of kaolinite in the entire Ione system, including proximal stream deposits and source rocks. This approach is based on the premise that an understanding of the micromorphologic characteristics of kaolinite in source rocks of the Ione sedimentary system would facilitate development of criteria for the recognition of detrital kaolinite in sandstones from other parts of the basin and lead to an understanding of its mode of transport. Further, the conclusions of Gillam (1974) and Rodgers (1986) in labeling Ione kaolinite as authigenic are based primarily on the petrographic criteria of Wilson and Pittman (1977) noted earlier; however, the latter authors caution that "none of the criteria should be considered infallible". Therefore, a re-evaluation of the origin of kaolinite in the Ione Fm. appears warranted.

Detrital kaolinite is generally not considered to be an important constituent of bedload sediment in fluvial systems for the reasons proposed by Wilson and Pittman (1977). Consequently, no effort has been devoted to developing useful micromorphologic criteria for distinguishing detrital kaolinite in sandstones. The absence of such criteria makes it difficult to determine the relative importance of detrital vs *in situ* authigenic kaolinite in Ione sandstones and precludes reliable interpretation of kaolinite genesis.

Therefore, the goals of this study are to: 1) determine the potential for detrital kaolinite in the Ione depositional system (ie., did a credible source for it exist?); 2) determine the mode of transport of detrital kaolinite in the Ione fluvial system (in what form was it transported to the basin: suspended load? sand? aggregates?); 3) identify diagnostic micromorphologic features which allow detrital kaolinite to be distinguished from authigenic kaolinite; and 4) evaluate the relative abundance of detrital kaolinite vs. kaolinite derived from the post-depositional weathering of Ione Fm. sediments.

When pondering whether detrital kaolinite could be a significant constituent in the Ione Fm. as Allen (1929) contended, the first consideration is whether a plausible source of the unique detritus of the Ione Fm. existed at the time of Ione deposition. This source of Ione fluvial detritus would have consisted of little more than quartz, kaolinitic clay, and resistate heavy minerals. Further, kaolinite would have been the dominant clay mineral in the source rocks as kaolinite constitutes greater than 98% of the clay matrix composition of distal Lower Ione sandstones.

Wilson and Pittman (1977) cited such a monomineralic clay composition as indicative of authigenic clay formation under a specific range of subsurface physical and chemical conditions. They pointed out that detrital clay in sandstones in the form of altered argillaceous lithic fragments are typically polymineralic clay assemblages because they are derived from diverse lithologies and soil types. Therefore, to produce a sediment in which kaolinite is the predominant or the sole detrital clay mineral, kaolinite would necessarily have to be the major or sole clay component of soils in source areas.

Initially, this notion seems unlikely considering the current climate and wide variety of soil types in the region. Nevada City currently has a mean annual temperature of 15°C (59°F) with an average annual rainfall of 76 cm (30 in). Under this temperate climate, diverse soil types have developed on the diverse lithologies presently exposed on the slopes of the Sierras. However, conditions were dramatically different during the Early Tertiary. Globally warm and humid conditions existed in latest Cretaceous times and continued into the middle Eocene (Savin *et al.*, 1975; Wolfe, 1978; Frakes *et al.*, 1992). As a consequence of these climatic factors, the degree of surface weathering and soil development was more advanced as compared to modern temperate climate soils. Under warm-humid climatic conditions, kaolinite is a major secondary clay mineral resulting from a long period of chemical weathering (Chamley, 1989). Kaolinitic soils forming under warm-humid conditions include Alfisols, Ultisols, and Oxisols (Dixon, 1989). However, of these three soil types, only Oxisols contain kaolinite in the abundance necessary to satisfy the provenance requirements of the Ione Fm. sediments (Soil Survey Staff, 1975; Singer, 1979; Stoops, 1983). Therefore, the questions that must be addressed to determine if a credible detrital source for Ione kaolinite existed are: 1) did kaolinitic Oxisols occur in Ione source areas, and 2) did early Eocene climatic conditions favorable to Oxisol development exist over the entire region of Ione deposition?

Published Criteria for Distinguishing Detrital Clay in Sandstones

While detrital kaolinite is not considered a major component of coarse clastic sedimentary rocks, sandstone petrologists recognize that detrital clay in general is an important constituent of clastic sediments in the form of argillaceous lithic fragments. Wilson and Pittman (1977) are often cited for petrographic criteria for recognizing authigenic clay in sandstones; however, their work as well as that of Dickinson (1970) also includes useful criteria for the recognition of detrital clay. Wilson and Pittman (1977) stated: "detrital clay may form sand-sized or larger aggregates of clay minerals" and "detrital argillaceous lithic grains or soft aggregates of clay minerals in sandstones easily deform with burial compaction to form what appears to be matrix". In this occurrence, deformed detrital clay aggregates can be difficult to distinguish from pore-filling authigenic clay. Such deformed argillaceous aggregates were termed "pseudomatrix" by Dickinson (1970). The following petrographic criteria listed by these authors proved valuable for the evaluation of the occurrence of detrital kaolinite in Ione Fm. sandstones.

Wilson and Pittman (1977):

1) Clay aggregates have a low bulk density due to inherent microporosity. Therefore, detrital clay aggregates should be coarser than associated quartz and feldspar grains [ie., 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.

Dickinson (1970):

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'."

MATERIALS AND METHODS

Study Areas

Sampling for this study included severely weathered bedrock (potential source rocks), proximal Ione fluvial deposits, and distal Ione fluvial deposits. Specific locations of samples analyzed in this study are listed in Appendix E.

Samples of the lateritic paleosols developed on the bedrock below the Ione Fm. were obtained at the Manzanita hydraulic mining site near Nevada City (Fig. 4). Remnants of the Manzanita mine site straddle Hwy 49 on the north edge of town. The Nevada County government buildings currently lie in the west end of the excavated floor of the hydraulic works with the U.S. Forest Service headquarters building sitting at the east end. Most of the weathered bedrock described by Allen (1929) is now covered by colluvium and parking lots. Unaltered granodiorite bedrock is not exposed in the area. A continuous profile from the upper horizons of the paleosol down to the saprolite does not exist; however, various portions of the paleosol are sufficiently exposed in the area for study. Another important example of a local lateritic paleosol previously described by Bates (1945) was sampled at Jones Butte near the town of Ione (Fig. 5).

Samples of proximal Ione fluvial sediments were obtained from the ancestral Yuba River system in the Nevada City area. Exposures of Ione fluvial channel deposits of the ancestral Yuba River are more abundant and have better accessibility than do channel deposits of other Ione fluvial systems further to the south (Fig. 2). In addition, the geology of the ancestral Yuba River channel system has been studied by several previous workers and the channel boundaries and flow directions are reasonably well defined (Lindgren, 1911; MacGinitie, 1941; Jenkins, 1946; Clark, 1965; Bateman and Wahrhaftig, 1966; Yeend, 1974; Lawler, 1988). Proximal Ione fluvial deposits were sampled at the Manzanita site, and in other hydraulic mining pits at Quaker Hill, Gold Run, Scotts Flat, and near the mining town of Washington (Fig. 4).

Recent petrographic work on Ione Fm. sandstones (Gillam, 1974; Rodgers, 1986) focused on deposits at or near the Ione type locality (Turner, 1894). Examples of distal Ione fluvial deposits examined in this study were sampled both in the Ione area (Fig. 5) and at Lincoln (Fig. 2).

In addition, fluvial sediments and underlying weathered bedrock materials were sampled from exposures near the town of Baxter (Fig. 4) under the assumption that they were Ione Fm. deposits. However, petrographic analysis shows that these materials are actually late Eocene to Oligocene intervolcanic fluvial deposits which lie immediately above the Ione Fm. The results of petrographic analysis of these samples are applicable to this study and are also reported.

Methods

Since the focus of this study is the micromorphological investigation of clay, the primary analytical tools used were the scanning electron microscope (SEM), electron microprobe, and the optical petrographic microscope. In addition, X-ray diffraction (XRD) was used to determine the mineralogy of soil and sediment constituents.

Sample Collection and Transport

Many of the soil and fluvial sediment samples collected in this study were extremely friable and readily disintegrated at the outcrop when disturbed. Successful sample transport back to the laboratory was accomplished by carefully inserting the coherent samples in cloth or plastic sample bags and completely enveloping the intact material with disaggregated material of the same composition. The bags were snugly placed in boxes to prevent jarring during transport to the lab.

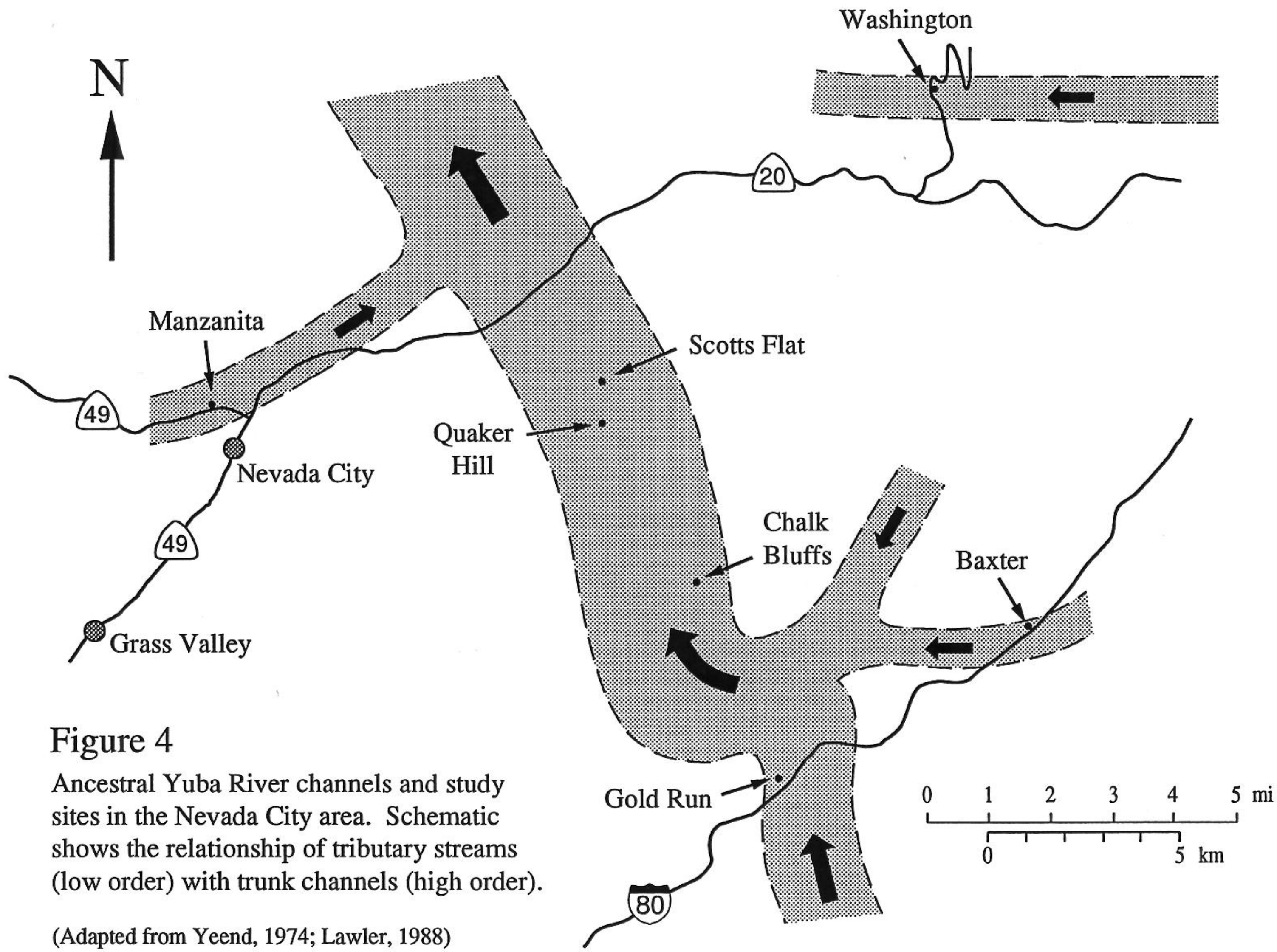


Figure 4

Ancestral Yuba River channels and study sites in the Nevada City area. Schematic shows the relationship of tributary streams (low order) with trunk channels (high order).

(Adapted from Yeend, 1974; Lawler, 1988)

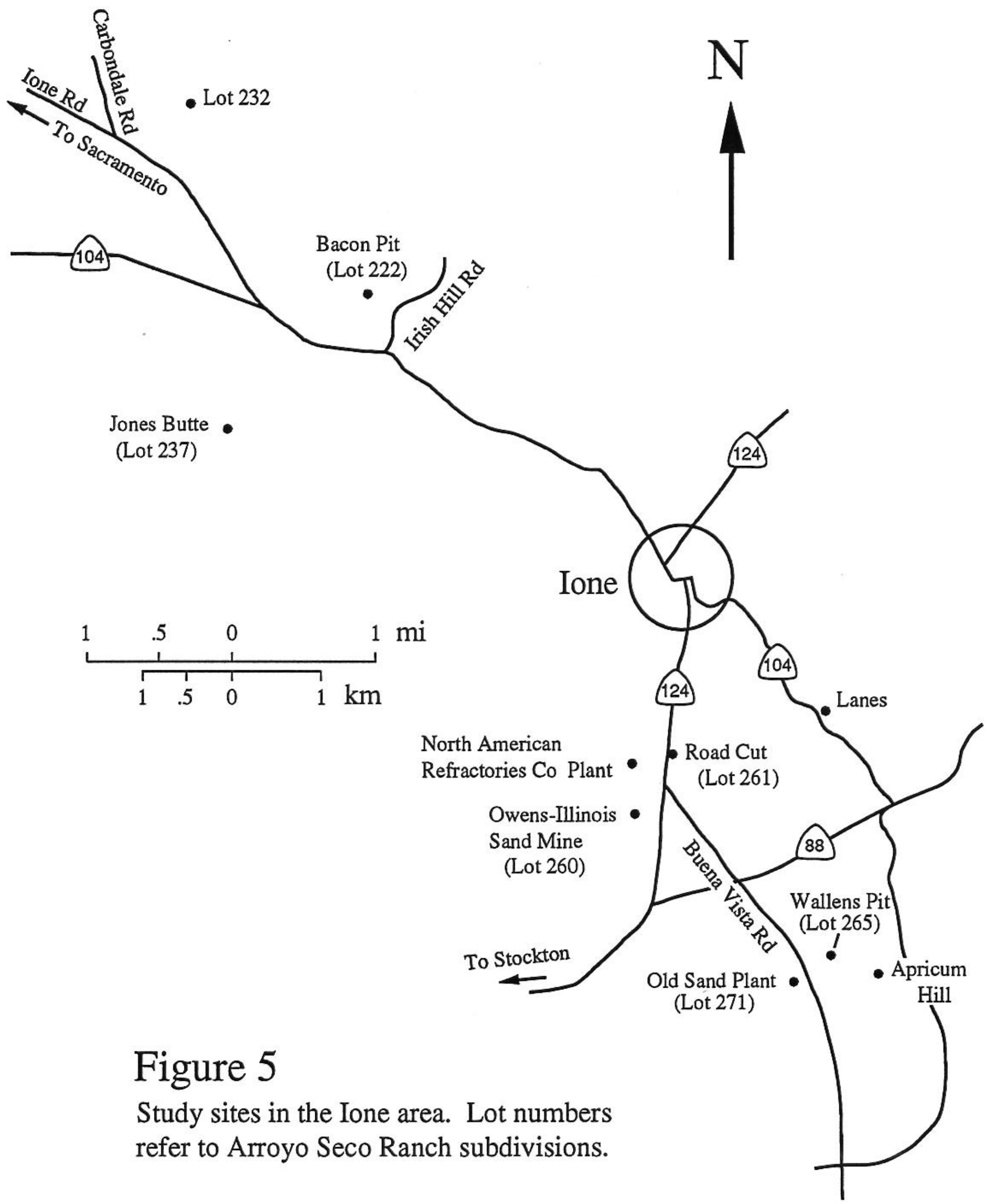


Figure 5

Study sites in the Ione area. Lot numbers refer to Arroyo Seco Ranch subdivisions.

Once in the laboratory, the bags were sliced open with a knife, and the coherent samples were gently removed. This technique proved successful for transporting friable samples by mail as well.

Thin Section Preparation Techniques

The friable, poorly consolidated samples of this study did not lend themselves directly to epoxy impregnation and initial attempts ended with complete disaggregation of the sandstone fabric. The solution to this problem was to first encase the friable material in a rigid epoxy shell by pouring epoxy resin over the coherent samples as they were extracted from the sample bag. This technique served the dual purpose of preserving the integrity of the rock fabric through subsequent steps in the thin-sectioning process and also preventing changes in volume which commonly occur in friable materials during epoxy impregnation. After the epoxy shell dried, the sample was ground on an abrasive lap or cut on a diamond masonry saw to expose a fresh unimpregnated interior surface and allow epoxy impregnation of the entire sample under vacuum.

Araldite® epoxy resin with 2% Automate Blue 8HF® dye was used both for the initial epoxy shell and subsequent steps to delineate porosity in thin section. Some thin sections were impregnated with non-fluorescent Buehler® epoxy resin for fluorescence analysis. The thin sections were finished on a diamond impregnated lap rather than with loose abrasive grit on a glass plate. Use of the latter method typically imbeds grit in the epoxy of the sample billet which leads to undesirable debris in the pores of the finished thin sections.

Thin sections were stained for feldspar using a two-stage staining technique (Friedman, 1971). Na-cobaltinitrate stains K-feldspar yellow and amaranth stains plagioclase pink or salmon colors.

Two important petrographic techniques used in this study proved crucial to enhance the observation of delicate clay micromorphologies. The first is the use of colored epoxy. In thin sections of kaolinitic materials impregnated with colorless epoxy, the fine details of kaolinite particle morphology are invisible in plane-polarized light (PPL). In addition, it is virtually impossible to distinguish kaolinite from colorless epoxy-impregnated porosity in sandstones (PPL). Colored epoxy solves these problems by infiltrating the microporosity inherent in kaolinite and delineating clay micromorphologies (ie., particle size and arrangement).

Thin sections are normally finished to 30 µm thickness. In such standard thin sections, very fine-grained kaolinite is, for practical purposes, nearly isotropic and has dark gray to black birefringent colors in cross-polarized light (XPL). Using standard thin sections makes detailed observation of kaolinite fabric difficult. However, kaolinite is not isotropic. A simple technique to increase the birefringent colors of such a low birefringent material is to make the thin sections thicker. Therefore, most of the thin sections in this study were finished to 50 µm. In thicker thin sections, kaolinite has birefringent colors ranging between gray and white depending on its particle size with the coarser clay crystallites appearing brighter. One must keep in mind that other minerals will have higher birefringent colors as well. For example, quartz appears orange to brown under cross-polarized light at this thickness. The advantage to using thicker thin sections is that the kaolinite morphologies and microfabrics are visible and even subtle variations are readily apparent.

Optical Microscopy

Optical petrographic observation of thin sections using plane-polarized (PPL) and cross-polarized transmitted light (XPL) was performed using a Zeiss Photomicroscope III. Photomicrographs were taken with Kodak Gold 400 ASA film. The reflectance of various mineral constituents was imaged by obliquely reflecting a high intensity white light source (WRL) on the thin section.

Organic matter was imaged in polished thin sections using a Zeiss MPM 400 microscope with blue reflected light excitation (BRL) using a HBO 100w high pressure mercury bulb. The 16x and 50x oil immersion objectives were used.

SEM

Initial work in this project was conducted using an AMRAY 1000 SEM at 20KV. Later work was done with an AMRAY 1910E SEM at 10-20KV. Useful magnifications ranged between 1000x and 5000x to image clay micromorphologies. Energy dispersive X-ray analysis (EDX) was performed to determine micro-chemical compositions using a Link ISIS X-ray energy spectrometer.

Electron Microprobe

Polished thin sections were coated with carbon and analyzed in backscattered electron mode (BSE) with a JEOL 733 Superprobe at 15KV with a beam current of 6 nanoamps. EDX analysis was performed with a 2 μm focused beam using a NORAN Series II X-ray system with a beryllium window over an X-ray collection range of 0-10 KEV. Useful magnifications ranged from 50x to image gross rock fabric up to 5000x to image clay microfabrics.

X-Ray Diffraction

X-ray powder diffraction analysis was used to determine mineralogy. Whole rock mineral analysis was performed using randomly packed powder mounts. Oriented samples were prepared for XRD analysis by dispersing the disaggregated sample with Na-hexametaphosphate and isolating various size fractions using centrifugation. Samples were then Mg-saturated by washing 3 times with 0.5*M* $MgCl_2$ followed by 3 washes with distilled water to remove excess salt. Oriented clay slides were prepared by the paste method of Theissen and Harward (1962). Where necessary, K-saturated clay slides were prepared using 1*M* KCl in the previously described routine. Mg-saturated clay slides were analyzed both with ethylene glycol solvation and under 54% relative humidity (air dry). K-saturated clay slides were analyzed after heating at 110°C. The relative abundance of specific clay minerals was estimated using the technique of Moore and Reynolds (1989) in which the XRD data is compared with calculated clay mixtures generated using the clay computer modeling program Newmod© (R.C. Reynolds, Jr., 1985).

X-ray analysis was performed with a computer automated Phillips X-ray diffractometer using copper $K\alpha$ radiation at 44 KV and 28 ma. The Phillips goniometer was operated at 1 degree 2θ /min with a 1° diversion slit and a 0.15° receiving slit. The data were digitally collected.

RESULTS

The Manzanita Profile—A Credible Kaolinite Source?

Soil Profile Description

Saprolite. A thick lateritic paleosol underlies the Ione fluvial deposits exposed in the abandoned Manzanita hydraulic mine workings at the north edge of Nevada City. The saprolite or lower part of the lateritic paleosol developed on granodiorite bedrock below Ione fluvial sediments is best exposed along Coyote Road (Fig. 6). The Coyote Road exposure is a 2.0 meter profile of saprolitic material unconformably overlain by 0.5 meters of Ione fluvial sediments. The saprolitic material is pallid (white) but some of the material is stained with yellow (10YR 6/6, Munsell soil color chart) subhorizontal Liesegang bands produced by iron oxide cement (goethite) associated with paleo-groundwater fluctuations.

In this severely altered soil material, all weatherable minerals appear to have altered to massive kaolinite. Visual inspection suggests that residual quartz is the only remnant of the original granitic mineralogy. Mica "books" pseudomorphically altered to kaolinite and, together with quartz, retain their original positions of the precursor granitic fabric. This saprolite is probably equivalent to Allen's (1929) description of "lithomarge"—severely altered biotite hornblende granodiorite from an unknown location in the Manzanita mine.

As the position of saprolite occurs at the bottom of weathering profiles, scouring by the overlying Ione fluvial channel undoubtedly removed the overlying horizons of the paleosol at this location. The Ione sands are stained red (10R 4/8) by post-depositional weathering and are separated from the white saprolite by an abrupt contact. White saprolite rip-up clasts of a few centimeters in diameter occur as lag in the basal fluvial sands.

Oxic Horizon. The upper horizons of the Manzanita paleosol and overlying Ione fluvial sediments are exposed adjacent to the Nevada County public library (Figs. 6, 7 and 8). The most striking morphologic feature of the paleosol is an apparent subsurface oxic horizon—the most important diagnostic feature required of soils for classification as an Oxisol (Soil Survey Staff, 1975; Buol *et al.*, 1980; Stoops, 1983). Oxic horizons are severely weathered, red, iron oxide-rich soil horizons. They are roughly equivalent to what has been termed "laterites" and "Latosols"; however, not all weathering profiles to which these two terms have been applied, qualify as Oxisols (Buol *et al.*, 1980). Here, the oxic horizon is a 15+ meter layer of clay-rich material with massive structure. Quartz grains float in massive clay with no apparent remnants of the original granitic fabric. Reddish-brown mottling features (redoximorphic iron oxide segregations) are dominant in the outcrop. Their appearance ranges between diffuse masses and nodular segregations of a few centimeters in diameter. Colors range from red (10R 4/6) to yellowish red (5YR 5/8) on the Munsell soil color chart.

The oxic horizon exhibits a diffuse upper boundary through a thin yellow zone (7.5YR 5/8) and grades into a 1.0–1.5 m thick upper white pallid zone (Fig. 7). The pallid zone is unconformably overlain by Ione fluvial sands. The lower boundary of the oxic horizon with the underlying saprolite is covered by alluvium at this site.

Mineralogy

Saprolite. Although the saprolite retains the phaneritic fabric of the original granitic rock, whole rock XRD analysis of a thoroughly altered sample of saprolitic material (#90-06B) shows that all weatherable minerals apparently altered to kaolinite with only quartz remaining (XRD 1, Appendix B). In addition, XRD analysis indicates that kaolinite constitutes >98% of the clay size

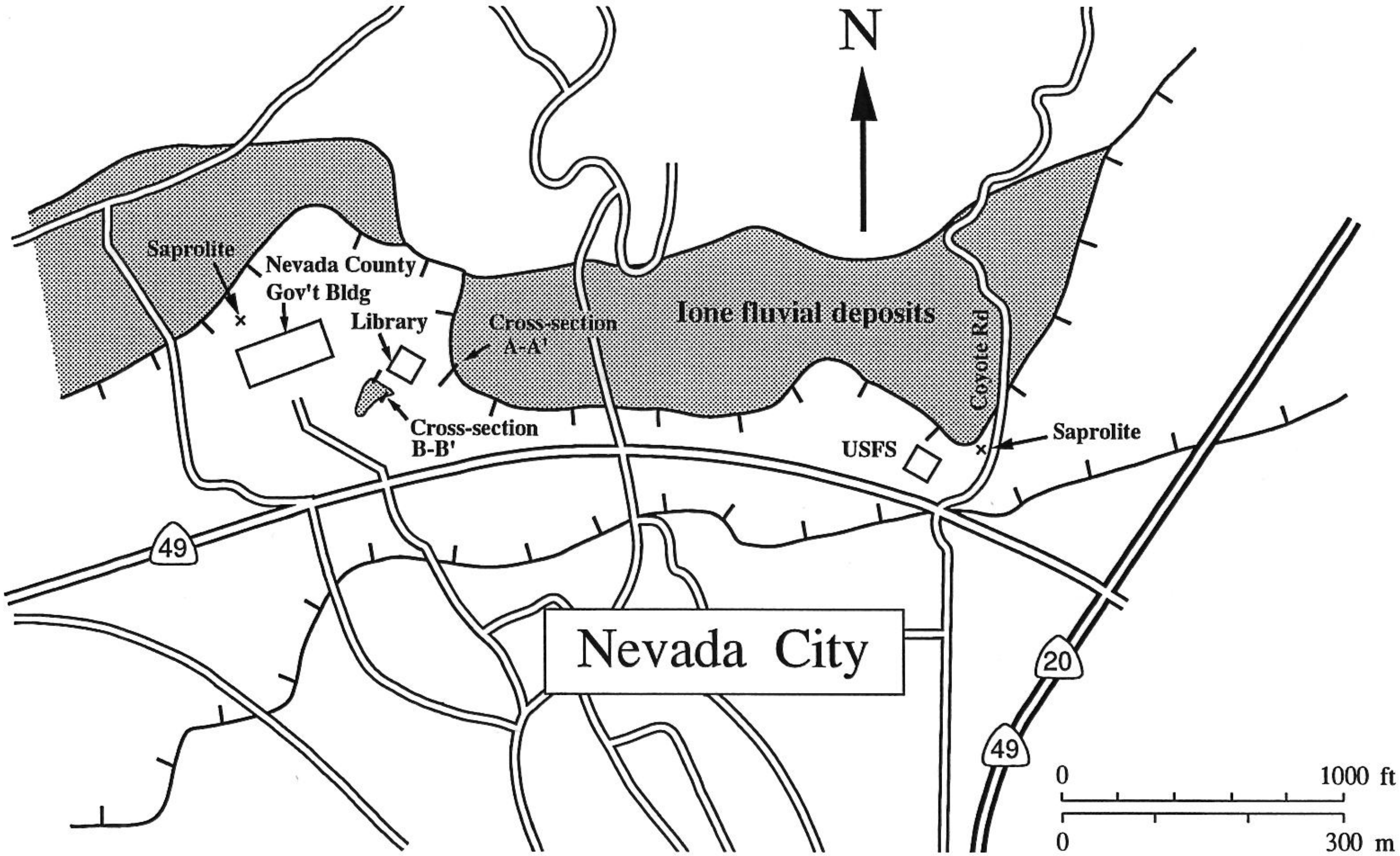


Figure 6

Location of study sites and cross-sections in the Manzanita mining pit at Nevada City. Hachured area indicates the margins of the Manzanita hydraulic mining activity.

(Mine pit boundaries from Yeend, 1974)

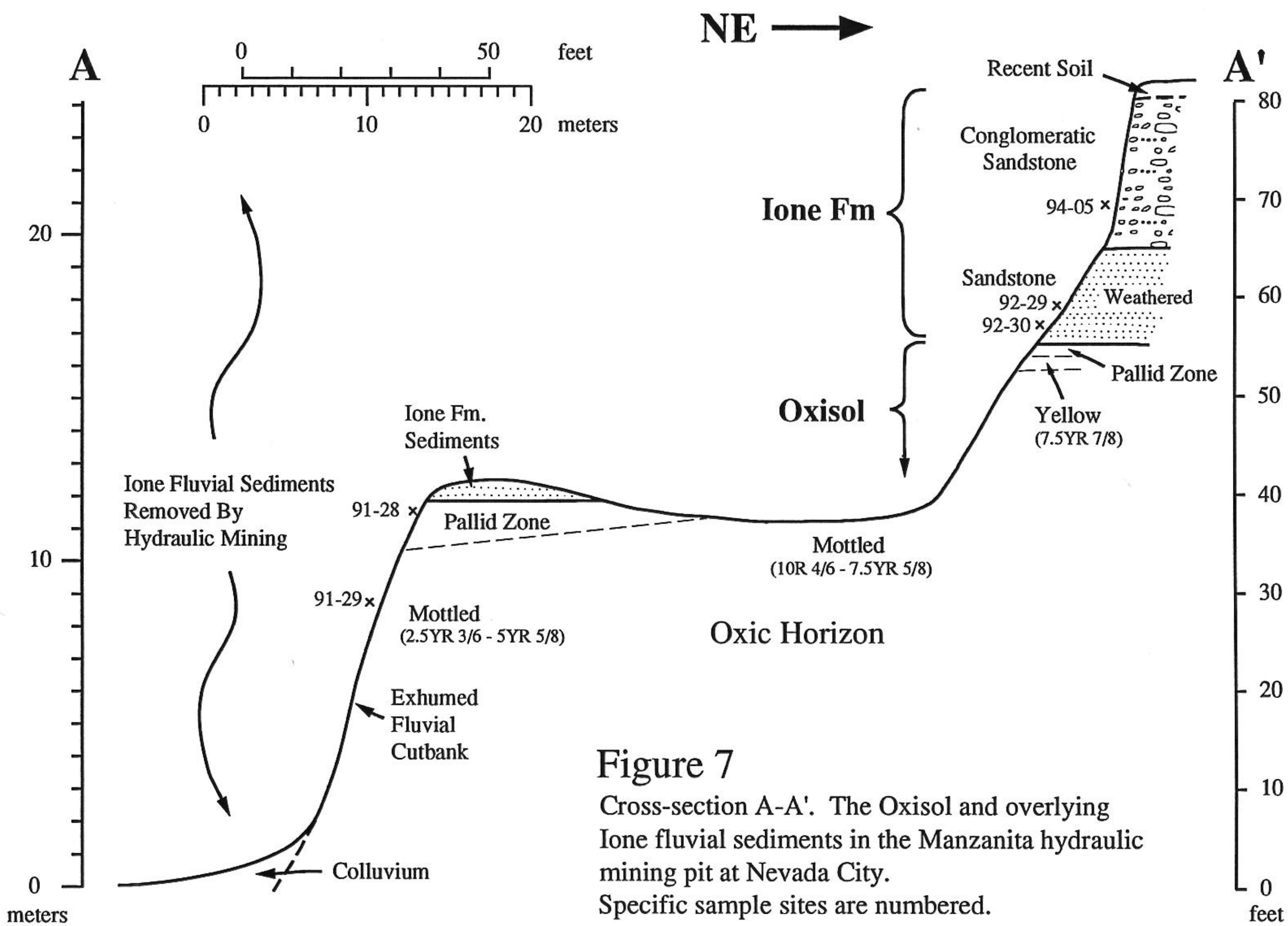


Figure 7

Cross-section A-A'. The Oxisol and overlying Ione fluvial sediments in the Manzanita hydraulic mining pit at Nevada City.
Specific sample sites are numbered.

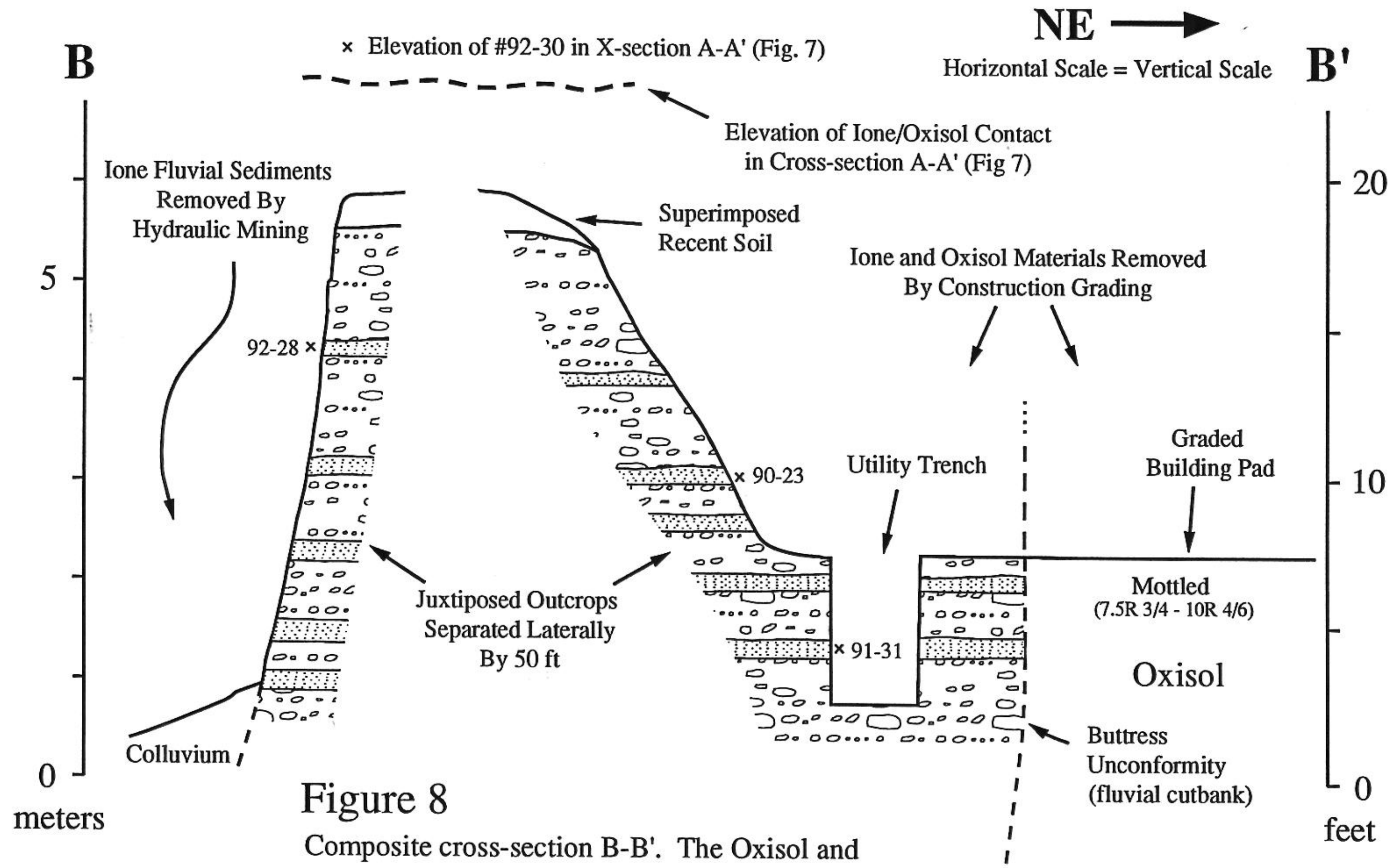


Figure 8

Composite cross-section B-B'. The Oxisol and adjacent Ione fluvial sediments in the Manzanita hydraulic mining pit at Nevada City. Specific sample sites are numbered.

fraction (<2 µm) with trace amounts of illite (mica) comprising the remainder (Table 1; XRD 3, Appendix B).

TABLE 1
Clay Mineral Abundance in the Clay Size Fraction (<2 µm) of Manzanita Oxisol Materials Determined by XRD

Sample ID	Horizon	XRD # (Appdx B)	Kaolinite %	Smectite %	Mica %	Other Minerals
91-29	oxic	3	98		tr	
90-06B	saprolite	3	98		tr	
94-06	saprolite	5	65	30	5	
90-10	saprolite	4	12	12	76	Ksp
90-10 (5–2 µm)		4	4	1	95	Ksp

Other symbols: Ksp = K-feldspar, tr = trace.

In thin section, the dominant minerals visible in the most severely weathered saprolitic material (#90-06B and #90-07) are kaolinite, kaolinized mica, and quartz. Except for trace amounts of remnant muscovite (sericite), other weatherable minerals such as feldspar are not apparent. The arrangement of quartz and kaolinized mica in the original granitic fabric is preserved (Photos 1 and 11, Appendix A). Although not detectable with XRD, thin section and microprobe analyses show that resistant accessory minerals including ilmenite, zircon, TiO_2 (rutile/anatase), and monazite occur in trace amounts. Compositions were verified using EDX analysis.

Resistant inclusions or xenoliths of partially weathered granitic material of up to a few centimeters in diameter are enveloped by completely altered saprolite material in the upper portion of the exposure. Visually, this partially weathered material appears to be composed largely of quartz and feldspar. XRD analysis of various size fractions of a sample of this partially weathered rock (#90-10) shows that it contains quartz, kaolinite, mica, and smectite with only a trace amount of K-feldspar (Table 1; XRD 4). Mica is more abundant in the >2 µm size fraction and smectite occurs mostly in the <2 µm size fraction. The bulk and clay mineralogy of partially weathered saprolite occurring in the lowest position of the roadcut exposure is similar to that of the isolated xenolith (#90-10) and shows the same trend of clay specie particle size distribution (mica >2 µm, smectite <2 µm).

Petrographic observation of the partially altered xenolith (#90-10) shows that euhedral feldspar crystals were completely sericitized. The resistant granitic xenolith probably had a mineralogy with greater abundance of quartz and K-feldspar than the immediately surrounding granitic rock and because of the greater resistance of these minerals to weathering (Goldish, 1938; Chamley, 1989), the xenolith was not completely kaolinized.

Another small exposure of saprolite is located on a hillside north of the Nevada County Government Building (Fig. 6). The original granitic fabric of this rock is also preserved. Although this saprolite material is pallid (white), it is not completely kaolinized and possesses a clay mineral assemblage composed of approximately 65% kaolinite, 30% smectite, and 5% mica (#94-06, Table 1; XRD 5).

Oxic Horizon. Whole-rock XRD analysis of mottled material in the oxic horizon exposed at the Library site (#91-29) shows that it possesses the mineral composition required for classification as an oxic horizon (Soil Survey Staff, 1975; Stoops, 1983). It consists of a mixture of kaolinite, iron oxides (goethite and hematite), and residual quartz (XRD 1). No other weatherable minerals are apparent in the whole rock XRD analysis. In hand specimen, kaolinite comprises much greater than 50% of the total volume of the oxic material—substantially in excess of the minimum 15% clay content requirement of Oxisols (Soil Survey Staff, 1975; Stoops, 1983). In addition, kaolinite comprises nearly 100% of the clay fraction (<2 µm) with only a trace amount of mica present (Table 1; XRD 3). Although cation exchange capacity (CEC) analysis was not performed, the low base cation saturation of this material is demonstrated by whole rock elemental analysis (WRA) using X-ray fluorescence (XRF). The WRA data of oxic material (#91-29) with elements summed as oxides (%) are as follows: SiO_2–46.8; Al_2O_3–27.7; CaO–0.09; MgO–0.13; Na_2O–0.02; K_2O–0.08; Fe_2O_3–11.8; MnO–0.02; TiO_2–1.13; P_2O_5–0.27; and Fe0–<0.1. These data collectively indicate that this material meets the morphologic and mineralogic criteria of an oxic horizon and would probably meet the USDA guidelines (Soil Survey Staff, 1975) for classification as an Oxisol.

Petrographic examination shows that kaolinite, quartz, and iron oxides are the dominant minerals in soil material in the oxic horizon. Trace amounts of muscovite also occur. Stoops (1983) reported that in other Oxisols studied, remnants of weatherable minerals such as feldspar or ferromagnesian minerals may occur in the oxic horizon if isolated by weathering crusts. No such occurrences of these weatherable minerals are apparent in the oxic material examined at this site.

Stoops (1983) reported that altered saprolite in Oxisols is transformed into oxic material of similar mineral composition but with homogenized soil fabric as a result of intense mechanical soil processes such as bioturbation and rooting activity—a process termed "pedoplasmation". He pointed out that the transition from saprolite to homogenized oxic material is gradual in granitic materials. This implies that the total thickness of the Manzanita Oxisol was probably much greater than the sum of the upper (oxic) and lower (saprolite) portions now exposed (~18 meters). This can be inferred from the fact that the upper zone of the truncated saprolite exhibits no morphologic similarities to material in the oxic horizon. One can only speculate as to the total thickness of the oxic horizon of this weathering profile or of the total thickness of the Oxisol that remains buried beneath the Nevada County library site.

As an illustration of the thicknesses Oxisols can attain, another local example of a lateritic paleosol is exposed at Jones Butte near Ione. Its oxic horizon alone is greater than 20 meters thick and the total thickness of this weathering profile was reported to be in excess of 30 meters (Carlson and Clark, 1954). The Jones Butte paleosol is clearly an Oxisol based on both the morphological characteristics of its oxic horizon and its mineralogy. Only kaolinite and iron oxides are apparent in whole rock XRD analysis of oxic material from this paleosol (#JB-1, XRD 2). Bates (1945) reported gibbsite in his analysis. Little or no quartz occurs in this severely altered material due, in part, to its low abundance in the andesitic precursor rock (Bates, 1945). Pisolitic iron oxide concretions are abundant in the oxic horizon of the Jones Butte weathering profile. The occurrence of pisolitic iron oxide segregations and gibbsite in the oxic horizon are probably indicative of a more advanced stage of weathering compared to the Manzanita paleosol.

Micromorphology

Saprolite. A prominent micromorphological feature of the saprolitic material originating from soil processes (pedogenic) is the development of open fissures (packing voids) throughout the clay fabric (Photos 1 and 11). The network of packing voids developed as a consequence of the passage of the large volumes of water through the soil fabric which facilitated the complete alteration of this rock through hydrolysis. The morphology of packing voids varies. Some of the voids are accommodated (both wall shapes match) while others are partially accommodated (terminology of Bullock *et al*., 1985). Others are chamber-shaped in which some of the matrix has dissolved. In advanced stages of development, the packing voids form a network which segregates the clay fabric into discrete sand-sized clay aggregates termed "micropeds" (Stoops, 1983).

Kaolinized mica books are a prominent kaolinite morphology in the saprolite. The kaolinite pseudomorphs, historically labeled "anauxite" (Allen, 1928), are up to 2 mm in diameter and appear in hand specimen as pearly-lustered white "books" and flakes. Some of the kaolinized micas preserve the precursor "book" morphology remarkably well (Photos 1 and 7). In other cases the replacement by kaolinite caused the original "book" structure to expand and degrade with the replacing kaolinite occurring as large vermicular forms within the original boundaries of the mica "book" (Photo 11).

The signal response (brightness) in backscattered electron images (BSE) is proportional to the total atomic weight of the particular compound or mineral. In the case of mineral polymorphs with the same composition, signal response is proportional to variations in density. Backscattered electron images of kaolinized mica grains show that alteration is incomplete in some and residual biotite layers with high titanium contents remain (Photo 8; EDX 1, Appendix C). Petrographic analysis of partially altered saprolite material shows that the high Ti contents of the precursor biotite was produced by rutile needles arranged hexagonally and perpendicular to the "c"-axis of the mica structure. Minute equant TiO_2 crystals (anatase) disseminated in the kaolinized portion of the pseudomorph may be an alteration product resulting from the dissolution of additional structural Ti in the mica.

The most noticeable feature of the kaolinite matrix of this "rock" is the heterogeneity of kaolinite micromorphologies. The kaolinite is segregated into numerous zones or domains which are comparatively heterogeneous to adjacent domains with respect to both grain size and particle arrangement (ie., discrete particles, stacks, vermicular crystals, etc.). However, within each zone, the kaolinite grain size and particle arrangement appears semi-homogeneous. These domains of differing kaolinite micromorphology can be distinguished from each other by contrasts in color density (PPL) (Photo 1) and by contrasts in birefringence (XPL) with zones of coarser grain size exhibiting higher birefringent colors. At low magnification, the boundaries between these domains appear relatively sharp but in high magnification BSE images, the boundaries show a slight transition or gradation between the micromorphologies of adjacent domains. The transition zones range up to 25 μm wide. The arrangement of these kaolinite domains are akin to the arrangement and grain boundaries of the precursor minerals in the original granitic fabric.

Burrows of micro-soil fauna can be seen in the fabric of the saprolite. In thin section, the undisturbed zones of clay fabric can be distinguished from bioturbated areas on the basis of color tone/density and particle arrangement. Undisturbed domains of kaolinite appear white and semi-homogeneous ("clean"), whereas, the bioturbated areas appear thoroughly homogenized and contain non-clay particulate matter (Photo 11). Consequently, these bioturbated areas have a darker ("dirty") appearance compared to the undisturbed clay zones. The bioturbated zones can also be recognized by other aspects of their microfabric. Although the clay particles in the burrowed areas appear randomly arranged (isotropic) and are nearly black (XPL), in transverse cross-sections (perpendicular to the axis of the burrow), a quasi-concentric particle arrangement is indicated by undulatory extinction (XPL). In longitudinal cross-sections, the burrows display parallel crescent-shaped particle alignment lines presumably produced by sequential backfilling by the burrowing organisms.

Back-scattered electron images dramatically show the variations in the kaolinite fabric. In saprolite material in which alteration is advanced but not complete (#90-07), these micromorphological differences among the domains are immediately apparent because of variable image brightness (Photo 2). Although not immediately apparent with the optical microscope, BSE images show that the boundary between many of the domains is marked by the occurrence of vermicular quartz (Photo 2). This remnant of the original granitic fabric is a feature termed "myrmekite". Myrmekite is an intergrowth of vermicular quartz and albite which without exception occurs near the margin of the albite crystals adjacent to grain boundaries with K-feldspar (Collins, 1988). High magnification BSE images show that the myrmekitic quartz resides within zones of fine-grained kaolinite fabric—the former site of albite, while the original position of K-feldspar grains is now occupied by domains of coarse-grained kaolinite characterized by vermicular and short stack morphologies. This relationship is the same for all occurrences of myrmekite in the saprolitic material.

SEM examination shows that in domains of fine-grained kaolinite, kaolinite particles occur as either randomly arranged discrete platelets, short stacks, or small vermicular forms with platelet diameters ranging between <1 and 5 µm (Photo 3). In zones of coarser grain size, large vermicular kaolinite forms are abundant with platelet diameters ranging from 10 to 25 µm wide and lengths of up to 100 µm or more (Photo 4). The vermicular forms exhibit longitudinal grooves that run the entire length of the vermicular particle. Backscattered electron images show that some of the platelets in the vermiforms are much brighter than kaolinite (Photo 5). EDX analysis shows that the darker material has the composition of kaolinite while the composition of the brighter layers is that of muscovite (EDX 2).

While the microfabric of kaolinite within a particular domain appears to be semi-homogeneous using optical petrographic techniques, SEM and BSE images reveal that the kaolinite microfabric within these "semi-homogenous" zones is actually heterogeneous in terms of particle size and morphology. For example, the larger kaolinite vermiform morphologies in the coarse-grained domains sit in a matrix of smaller discrete platelets and short stacks of kaolinite. The microfabric of both the coarser and finer grained zones can be described as an aggregate of coarse particles enveloped by a relatively finer grained matrix (Photos 3, 4, and 5).

Petrographic examination of the partially altered granitic xenolith in the Manzanita saprolite provides some insight into one of the pathways of secondary kaolinite formation in the saprolite. This partially altered material (#90-10) has a clay mineralogy of mica, kaolinite, and smectite as described earlier (XRD 4). Thin section examination shows that sericite now fills the euhedral outlines of former feldspar grains in the residual quartz fabric. The greater resistance of this saprolite material to weathering and the detection of a trace amount of K-feldspar in the XRD analysis (XRD 4) suggests that this granitic inclusion was probably originally comprised largely of quartz and K-feldspar. SEM views show sericite to be in the form of randomly arranged, irregularly shaped plates and flakes of about 5 to 25 µm in diameter (Photo 6). The sericite flakes are remarkably similar in shape and size to individual platelets in the large vermicular kaolinite forms that are abundant in the former sites of K-feldspar grains in the granitic saprolite (Photo 4). This, in addition to the fact that the vermicular kaolinite contains residual mica layers of the same size (Photo 5), supports the premise of Pevear and Nagy (1993) that vermicular kaolinite forms by replication using mica platelets as a template. They termed this occurrence—"copy-cat" kaolinite (Fig. 9). Although Pevear and Nagy (1993) initially applied this vermicular kaolinite model to diagenetic kaolinite in sandstones that contain detrital mica, this alteration mechanism apparently operates in soil weathering environments as well.

Pedogenic cements are also an important component in the fabric of the saprolite material. Some areas in the kaolinite matrix are paler than the surrounding blue epoxy impregnated kaolinite fabric (PPL). These areas of fabric are saturated with a cement that fluoresces dull yellow to orange yellow with blue reflected light (BRL) excitation (Photo 12). Areas of kaolinite fabric impregnated with this pale-fluorescent cement (P-F cement) are as large as 1.0 mm in diameter. P-F cement is not restricted to the clay fabric alone, but also fills fractures in quartz grains in the affected zones of the saprolite fabric (Photo 12). In this occurrence, high magnification views show that the boundary of the fracture-filling P-F cement against porosity is often in the form of a concave-shaped meniscus that drapes between the walls of the fracture.

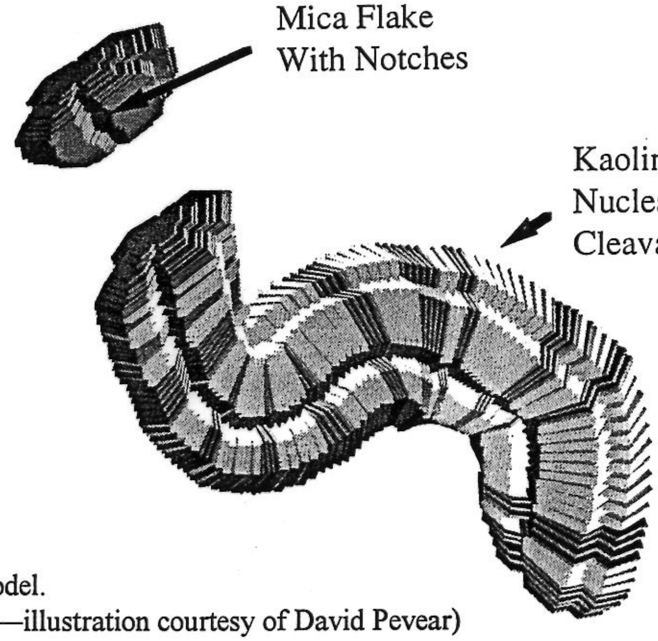


Figure 9
Vermicular Kaolinite Model.
(Pevear and Nagy, 1993—illustration courtesy of David Pevear)

Other zones of cemented kaolinite matrix appear opaque (black) in transmitted light (PPL) and have a diffuse pale yellow to cream color with oblique white reflected light (WRL). The opaque cement also fluoresces in colors ranging between bright and dull yellow (BRL). In addition, this opaque-fluorescent cement (O-F cement) saturates kaolinized micas and occurs in the form of elongate (0.1 mm by 2.0 mm), sinuous coatings throughout the kaolinite matrix. The O-F cement also occurs as spherically shaped coatings forming enclosures ("quasi-coatings" of Bullock *et al.*, 1985) and micronodules concentrated in the center of some of the micropeds segregated by the packing void network (Photo 11).

Analysis of the kaolinite fabric saturated with these fluorescent cements using EDX shows higher Si/Al atomic ratios compared to the ideal 1:1 Si/Al ratio of kaolinite. Silica enrichment in these cemented zones is indicated by Si/Al ratios ranging between 1.15 and 1.25 calculated from digital peak height data (EDX 3). In addition to higher Si contents, EDX analyses show that these cements may contain trace amounts of Fe, K, and Ca. Chlorine was detected in other examples.

In BSE analysis, the fluorescent cements are recognized as amorphous material of lower signal response (brightness) which drapes between both coarse- and fine-grained kaolinite particles (Photo 9). These cements enhance the aggregate nature of the pedogenic kaolinite microfabric and probably contribute to clay aggregate stability. Areas of kaolinite fabric with higher concentrations of O-F cement exhibit a unique pattern characterized by a network of ultrafine spherical voids—a microfabric that could be described as "spongy" (Photo 10). The morphology and distribution of the ultrafine voids (microvoids) suggests that the O-F cement was emplaced as a soluble liquid with a high surface tension causing it to drape between kaolinite particles and, thus, giving the appearance that it entrained a myriad of ultrafine bubbles. The backscattered electron images show that the "spongy" microfabric of O-F cement is associated with loosely packed arrangements of kaolinite particles. The siliceous cements saturating the loosely packed kaolinite fabrics were probably of insufficient volume to completely fill the interstices between the clay particles. Consequently, microvoids were preserved in the cement matrix at the time of precipitation or "gelling". The shape of sinuous coatings and micronodular morphologies of O-F cement with which this peculiar "spongy" microfabric is associated, indicates that it is not an artifact of thin section polishing.

The opaque appearance of O-F cement is probably a consequence of the peculiar "spongy" microfabric. Large voids (bubbles) embedded in the epoxy resin of thin sections appear as grains of high relief and are nearly opaque to transmitted plane-polarized light because of light reflection and refraction. Clay fabric containing siliceous cement and its multitude of entrained microvoids probably scatters transmitted light in an similar manner. This would occur because of the large difference in the refractive index between the siliceous cement and the voids. In zones with high concentrations of O-F cement and its "spongy" microfabric, significant light scattering would cause light "shadows" or opaque appearing zones with transmitted light (Photo 11).

The unique diffuse pale yellow or cream color of O-F cement in white reflected light (WRL) is also probably the result of the microvoids entrained by the O-F cement. Large bubbles in epoxy resin appear bright yellow (WRL) because of light dispersion. The same phenomenon yields a diffuse pale yellow or cream color (WRL) on the surface of the O-F cemented zones with its multitude of microvoids. The O-F cement exhibits a similar yellowish color with a high intensity white light source obliquely illuminating the underside of the thin section.

Larger discrete opaque particles are associated with the occurrence of this fluorescent cement in zones of kaolinite with larger particle sizes and loose packing arrangements. The siliceous cement apparently seals some of the large pores between clay particles without completely filling them leaving larger voids dispersed in the clay fabric. In thin section at low magnification, these voids appear as opaque particles of high relief (Photo 1). The large opaque particles (voids) appear bright yellow with white reflected light. BSE images verify that the opaque particles are actually voids and not heavy minerals. The larger voids form a grain size continuum with the microvoids appearing as diffuse O-F cement suggesting that these opaque morphologies are purely a function of the particle size and packing arrangement of the clay fabric. The petrographic manifestation of the siliceous-rich cement as opaque particular and diffuse morphologies could be easily mistaken as an occurrence of authigenic minerals with high relief such as sphene.

The difference in the appearance of pale vs opaque cement is probably also a function of the structure of the kaolinite microfabric in which the pale cement occurs. SEM images show that the P-F cement coatings are associated with a kaolinite microfabric with a denser packing arrangement of platelets compared to fabric permeated with O-F cement. The solutions which saturated the tight kaolinite fabric probably completely filled the interstices between the platelets and, consequently, no inhibition of light transmission occurs. This cement would also have caused the exclusion of blue epoxy—hence, the pale appearance.

These fluorescent siliceous-rich zones and coatings were analyzed using infrared reflected light spectrometry (IR) by Pradeep Iver at UNOCAL Science and Technology Division, Brea. IR analyses show that these fluorescent cements possess an IR signature indicative of trace amounts of aliphatic and aromatic compounds. These are both common constituents of humic substances in soils. The association of organic matter with the siliceous cements suggests that the organic matter is tied to the amorphous inorganic compounds of the cements as a stable organo-siliceous complex. Organic compounds in solution in the soil such as humic acids commonly form stable complexes with amorphous inorganic colloids—components of the soil leachate (Fieldes and Claridge, 1975; Oades, 1989).

The fluorescent signature of these siliceous cements is intriguing (Photos 12 and 14). The fluorescence is not an inherent property of amorphous silica but can be produced by trace concentrations (ppm range) of aromatic hydrocarbon compounds (Rui Lin, Unocal Science and Technology, personal communication, 1994). The results of IR analysis showing the presence of aromatic compounds provide corroborative evidence that the fluorescence associated with the siliceous cement is produced by trace amounts of the aromatic component of organic compounds that are probably complexed with the amorphous silica.

Aromatic hydrocarbons and methylene-containing (CH_2) aliphatic compounds are normal components of humic substances derived from the degradation of humus in the organic layer at the top of the soil profile (Schnitzer and Kodama, 1977). When humic acid enters the ground water, it can form stable complexes with amorphous inorganic colloids which are components of the leachate (Fieldes and Claridge, 1975; Oades, 1989). The complexing of organic acids with amorphous siliceous compounds probably increases their solubility and, thus, enhances the ability of these solutions to move through and saturate the clay fabric before precipitating (Rui Lin, personal communication). Drees *et al.* (1989) cited the work of Evans (1965) and Crook (1968) who showed that the presence of organic molecules in the soil leachate increases the solubility of silica and that silica goes into solution as an organo-siliceous complex (Crook, 1968; Cleary and Conolly, 1972). Upon precipitation, these organic-inorganic complexes form gels which add considerable stability to clay aggregates in soils (Fieldes and Claridge, 1975; Oades, 1989). After the siliceous compounds convert to opal, the chemisorbed organic C decreases the solubility of opal and increases its stability (Drees *et al.*, 1989).

The composition of humic substances in the soil may be quite variable (Oades, 1989). According to Lin (personal communication), the blue reflected light fluorescence technique is sensitive to slight changes in both the composition and concentration of organic matter. Compositional variability of complexed aromatic compounds probably accounts for the variations in the fluorescent colors exhibited by the amorphous cements saturating the kaolinite fabric of the Oxisol.

<u>Oxic Horizon</u>. Kaolinite micromorphologies that occur in the saprolite persist in material of the oxic horizon at the Library site (Fig. 7). The notable difference between the two is the greater degree of bioturbation from burrowing organisms and, consequently, the greater volume of kaolinite fabric that has been homogenized in the oxic horizon.

The development of void space and packing voids is significantly greater in the oxic horizon compared to the saprolite. Development of packing voids was promoted by shrinking and swelling of the clay fabric as a consequence of the alternating wet and dry periods of the Early Tertiary tropical climate. The network of packing voids segregates much of the clay fabric into sand-sized micropeds (Photo 13). Stoops (1983) reported that the occurrence of sand-sized micropeds in the fabric of the oxic horizon is typical of Oxisols. He explained that rounded micropeds are produced when microfissures progressively develop to become a network of packing voids. He noted that as a consequence of extensive microped development, the oxic horizons of many Oxisols possess a granular or sandy consistency ("pseudosand"). In the Manzanita oxic material, the packing voids range in appearance between accommodated simple packing voids to larger unaccommodated, smooth-walled channels and chambers (terminology of Bullock *et al.*, 1985) (Photo 13).

Thin section examination shows that the structure of micropeds can be complex. Many are enveloped with a P-F cement coating which concentrically lies within the margin of the micropeds ("quasi-coatings" of Bullock *et al.*, 1985) (Photo 13). These coatings fluoresce dull yellow similar to those which occur in the saprolite (Photo 14). Some micropeds have an additional concentric O-F cement coating located on the interior of the outer P-F coating (Photo 13). As in the saprolite, this O-F cement coating exhibits a diffuse pale yellow color in white reflected light and has a yellow fluorescent color in blue reflected light (Photo 14). In other micropeds, the O-F cement is concentrated in the center (Photos 13 and 14). This latter morphology is similar to micronodular occurrence of O-F cement in micropeds in the saprolite as discussed earlier (Photo 11).

In thin sections stained for feldspar, as were many in this study, plagioclase stain infiltrated the interior of some of the micropeds and stained the interior clay fabric red (Photo 13). This happened because the enclosing organo-siliceous cement coating was effective in sealing off the interior of the micropeds from epoxy impregnation. Thus, when the thin section was cut and finished, the stain invaded the unimpregnated clay fabric in the core of the microped. In thin sections not stained for feldspar, the unimpregnated clay fabric appears brown (Photo 11). This artifact of sample preparation serves to illustrate the spherical nature of the micropeds. Hence, the term "spherical micropeds" used by Retallack (1990) appears appropriate to describe these pedogenic features.

Two observations suggest that the organo-siliceous cement that invaded the microped clay fabric originated from solutions moving through the fissures. First, the organo-siliceous cement invaded the clay fabric symmetrically the same distance from the packing voids (Photo 13). In addition, the organo-siliceous cement coatings appear to be in similar stages of development in adjacent micropeds throughout a given region of fabric. These observations suggest that siliceous-rich solutions in the groundwater saturated the entire region of the soil fabric (at least within the region encompassed by the thin section) simultaneously.

Using EDX analysis, trace amounts of Fe and other cations were identified as components of the organo-siliceous cements which saturate kaolinite in the saprolite and oxic horizons (EDX 3). Humic acids are known to form stable soluble complexes with metallic ions such as Fe, Ca, and other cations (Schnitzer and Kodama, 1977; Stach, 1982; Oades, 1989). Chelated iron bound in such an organic complex will remain stable unless oxidation of the organic matter occurs (Schnitzer and Kodama, 1977; Schwertmann and Taylor, 1989; Oades, 1989). When organic matter is oxidized, chelated iron is released and the precipitation of iron oxides results (Oades, 1989; Schwertmann and Taylor, 1989). The oxidation of organic matter complexed with amorphous silica cement in kaolinite appears to play a role in controlling the distribution of iron oxide phases precipitating in the oxic horizon.

Schwertmann and Taylor (1989) showed that the slow release of chelated iron resulting from the oxidation of organic matter in soil materials favors goethite precipitation over hematite. This is because the slow release of iron inhibits the formation of ferrihydrite, the necessary precursor of hematite. They noted that hematite precipitation is favored if the rate of iron availability increases either because of the rapid oxidation of organics with higher soil temperatures and better aeration or from influxes of additional iron from other sources.

This mechanism may explain the distribution and association of iron oxide phases with organo-siliceous cement in oxic horizon materials (#91-29). Petrographic examination shows that disseminated goethite cement occurs on the interior of some kaolinite aggregates permeated with siliceous cement in an area isolated from packing pores (Photo 15). This suggests that the slow oxidation of organic matter complexed with silica cement favored goethite precipitation at this site. In contrast, hematite precipitation is focused in areas adjacent to fractures and packing pores. At these sites either aeration was better or pore water solutions brought in additional iron. Streaks of hematite also appear to be associated with zones of higher concentrations of organo-siliceous cement (Photo 15).

Upper Pallid Zone. The clay fabric in the pallid zone above the oxic horizon is nearly completely homogenized (#91-28). Petrographic observation shows that quartz grains are evenly disseminated in the fabric. SEM images show that the clay fabric typical of this horizon is comprised of randomly arranged kaolinite particles (Photo 17). Organized kaolinite morphologies such as vermicular forms and stacks are uncommon. These were apparently disaggregated by mechanical soil processes as bioturbation patterns in the clay fabric are ubiquitous. One notable exception is the occurrence of abundant kaolinized mica books that endured the homogenization process and were apparently resistant to the mechanical forces imposed by faunal and rooting activity (Photo 16). Their grain margins appear sharp with no apparent degradation. Some kaolinized mica grains are saturated with O-F cement which imparts a dusty appearance to them.

O-F cement coatings are abundant and form sand-sized subspherical enclosures in the homogenized clay fabric. This same fabric superimposed with iron oxide (goethite) cement is typical of soil material in the thin yellow colored transition zone that separates the upper pallid zone from the underlying oxic horizon (Fig. 7).

Illuvial pore-lining clay coatings (ie., clay skins, cutans, argillans, etc.) produced by translocated colloidal clay particles are not apparent in this upper pallid zone nor do they occur in the underlying horizons. The absence of illuvial clay is typical of the oxic horizon of Oxisols (Soil Survey Staff, 1975; Buol *et al.*, 1980; Stoops, 1983). These authors attributed the near absence of illuvial clay in Oxisols to factors such as the intense homogenizing soil processes occurring in the oxic horizon as well as the stability and immobility of kaolinite and the general absence of other water dispersible clays such as smectite.

Discussion

Soil Classification. Evidence indicates that the Manzanita weathering profile possesses most of the physical, mineralogical, and micromorphological characteristics of oxic horizons and probably should be classified as an Oxisol.

The Manzanita soil profile possesses the following characteristics of oxic horizons outlined by the Soil Survey Staff (1975):

1) The horizon is greater than 30 cm thick.
2) It does not contain more than trace amounts of weatherable minerals including feldspar, mica, and ferromagnesian minerals.
3) It contains greater than 15% clay in the fine earth fraction (<2 μm).
4) It has gradual or diffuse boundaries between subhorizons.
5) Less than 5% of the horizon possesses rock (saprolite) structure.
6) Cation exchange capacity—the profile probably meets the cation exchange capacity requirement of an oxic horizon because the clay assemblage is dominated by kaolinite with little or no smectite and also because elemental analysis shows a low base cation content.

In addition, the Manzanita profile possesses key micromorphological characteristics of oxic horizons listed by Stoops (1983):

1) Only trace amounts or absence of weatherable minerals in the sand and silt fraction.
2) Absence or low amount (<1%) of illuvial clay (cutans, argillans).
3) Microped structure.

A Credible Kaolinite Source. Based on mineralogical composition, the Manzanita paleosol and related tropical soils were a credible source of the kaolinitic clay in the Ione Fm. The question remains as to whether there was sufficient volume of kaolinitic source materials to supply the quantity of kaolinite contained in Ione sediments. The regional extent of kaolinitic oxic material in Ione source areas would have depended on the Eocene climatic and topographic factors favoring laterization. This question can be addressed by understanding the regional early Eocene climate.

Today, Oxisols develop in low latitude intertropical areas of the world with high temperature and rainfall regimes. 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, or isothermal conditions ("equable").

Allen (1929) and all the other early workers who referred to the weathered residuum mantling the bedrock underlying Ione fluvial deposits as "laterite", recognized the tropical climatic conditions required for its development. Corroborative evidence of a warm and humid early Eocene climate in the region is provided by paleobotanical studies of fossil folia preserved in Ione channel mudstones exposed in a hydraulic mining site located at Chalk Bluffs (Fig. 4). MacGinitie (1941), working with specific fossil plant genera, concluded that a "tropical rain forest" plant association existed in the central Sierras during the early Eocene. He cited the Sierra Madre rain forest areas of Southern Mexico as a modern analogue to the Sierran early Eocene climate. He stated the characteristics of this equivalent tropical climate regime as follows: 1) frostless; 2) "equable"—the average temperature of the warmest and coldest months differs by less than 7°C (12°F); 3) most of the precipitation occurs during the summer months with periodic dry periods in the winter; and 4) average annual rainfall of >200 cm (84 in.) vs. 76 cm (30 in) at Nevada City today.

Later paleobotanical work by Wolfe (1978) on fossil Eocene folia from near Susanville, California, further north in the Sierras, confirmed MacGinitie's (1941) earlier conclusions. Wolfe's (1978) results were based on studies of fossil foliar physiognomy (leaf shapes). His work shows that plants with particular physical characteristics including leaf shapes will adapt to a specific climate. Consequently, plants adapted to similar climates but in separate locations or from different time periods will have leaf assemblages with similar physical characteristics. Thus, the physical characteristics of a fossil leaf assemblage can be compared to modern analogues to get an indication of the paleoclimate. He also equated the Eocene climate in the ancestral Sierras to the tropical forest lowlands of Southern Mexico. He estimated an early Eocene mean annual temperature in the Central Sierras of 27°C (81°F) vs 15°C (59°F) today.

Wolfe (1978; 1985) contended that warm-humid conditions (those that favor Oxisol development) existed in the mid-latitudes of North America in the Early Tertiary 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 is another indication that they were probably ubiquitous on the Early Tertiary landscape. Late Cretaceous to Early Tertiary tropical soils dominated by kaolinite have been reported in Baja (Peterson and Abbott, 1979), buried under sediments near Iceland (Nilsen and Kerr, 1978), throughout the southeast United States (Sigleo and Reinhardt, 1988), and in Minnesota (Goldish, 1938; Parham, 1970) to name but a few.

Other conditions required for the formation of Oxisols give a clue as to whether their occurrence was patchy or widespread in Sierran source areas. The mineralogy and morphology of mature Oxisols and their diagnostic oxic horizon can take up to 10^6–10^7 years to develop—the longest period of time of all soil types (Birkeland, 1984; Retallack, 1990). The long period of continental stability in areas where Oxisols occur (Soil Survey Staff, 1975; Buol *et al.*, 1980; Retallack, 1990) is intuitive considering the great depth of chemical weathering that occurs in Oxisols and the long period of time required for their development. These authors also point out that Oxisols are typically found on topography of relatively low relief. Allen (1929) noted that the topography associated with the deeply weathered Early Tertiary paleosols in the ancestral Sierras was also one of gentle slopes and low relief.

Favorable climatic and topographic conditions for the development of Oxisols existed in the region of the ancestral Sierras during the Early Tertiary (Allen, 1929; MacGinitie, 1941; Wolfe, 1978, 1985). Therefore, it is not surprising that Allen (1929) found deeply weathered kaolinitic paleosols immediately below the Ione Fm. over its entire extent in exposures where the underlying bedrock contact was visible. He reported either the presence of an underlying oxic horizon ("laterite") or deeply weathered kaolinitic saprolite ("lithomarge") in cases where Ione fluvial scouring had removed the upper portion of the paleosol. Many of the underlying lateritic paleosols discussed by Allen (1929) and other early workers would probably be classified as Oxisols using current criteria. For example, the deeply weathered lateritic paleosol at Jones Butte near Ione (Fig. 5) described by Allen (1929) and later by Bates (1945) is clearly an Oxisol based on the characteristics of its diagnostic oxic horizon and mineralogy (XRD 2).

Realizing that hundreds of square miles of the ancestral Sierras were probably mantled with 20–30 meters or more of kaolinitic weathered residuum during the early Eocene, source area soils probably held a sufficient reserve of kaolinitic material to account for the volume of kaolinite in the Ione Fm fluvial and deltaic deposits.

Kaolinite Micromorphological Diversity. One important result of this petrographic examination of the Manzanita Oxisol is learning of the great diversity of kaolinite micromorphologies occurring in the soil fabric. In addition to forming soil aggregates composed of varying microfabrics, kaolinite occurs as sand-sized pseudomorphs of mica and as thoroughly homogenized material at the top of the soil profile. The occurrence of such a complex arrangement of kaolinite microfabrics at first seems inexplicable. However, in the case of kaolinized mica, kaolinite pseudomorphed large mica books because of the similarity of the phyllosilicate structures of the two minerals. The ability of kaolinite to mimic the morphology of the phyllosilicate precursor may offer an important clue as to the controlling factor of kaolinite particle morphology in deep weathering environments.

Kaolinite may ultimately be a stable alteration product of chemical weathering in many tropical soils; however, in the weathering front in the lower portion of the saprolite, other phyllosilicates commonly form prior to kaolinite as unstable intermediate weathering phases (Chamley, 1989). For example, kaolinite may be the only clay mineral in surface horizons of a tropical soil developed on mafic rock, however, smectite may be the dominant clay mineral at the weathering front of the saprolite and kaolinite may not even be present as in the case of the kaolinized Cretaceous Morton Gneiss in Minnesota (Parham, 1970). This is because in the weathering front, hydrolysis is not as severe as in the upper portions of the Oxisol and sufficient cations may be available to precipitate 2:1 layer silicates (ie., smectite, vermiculite, sericite, mixed-layer clays, etc.) depending on the composition of the minerals being dissolved (Chamley, 1989). Eventually as the weathering front moves deeper in the soil profile, kaolinite will begin to precipitate and ephemeral intermediate clays will dissolve because of greater hydrolytic activity. Consequently, the particle size of the transitory intermediate phyllosilicate phase that kaolinite replaces may determine the micromorphology of secondary kaolinite analogous to the kaolinite pseudomorphs of mica books.

Sericite serving the role as a template for kaolinite precipitation satisfactorily explains the irregular configuration and dimensions of the vermicular kaolinite platelets and the longitudinal grooves replicated along the entire length of the crystal. Pevear and Nagy (1993) suggested that these latter features were likely created as precipitating kaolinite replicated re-entrants or notches in the irregular shape of the mica template (Fig. 9). It is not clear if the sericitization of feldspar in the Manzanita saprolite occurred at an early stage (ie., deuteric alteration) or as a consequence of low temperature surface weathering. Nevertheless, sericite is reported to be an unstable intermediate phase in the weathering of K-feldspar to kaolinite (Huang, 1977; Chamley, 1989). Petrographic analysis of fresh unweathered granitic rock at the Manzanita site would put this question to rest.

Likewise, the intermediate smectite phase altering to kaolinite probably played a similar role in determining subsequent kaolinite particle size. Smectite is known to be an transitory intermediate phase of albite and other mafic minerals weathering to kaolinite (Huang, 1977; Chamley, 1989).

These latter minerals were common in the biotite hornblende granodiorite precursor of the Manzanita saprolite. In the Manzanita saprolite, smectite occurs mostly in particle sizes less than 2.0 µm. The occurrence of finer grained kaolinite in sites known to be formerly occupied by albite based on myrmekite relationships suggests that the smaller particle size of the precursor smectite may indeed have played some role in determining the micromorphology of the kaolinite end product.

Various minerals have differing pathways in weathering to the kaolinite end product depending on their specific mineral composition (Chamley, 1989). In this Manzanita saprolite, the variability of kaolinite micromorphologies is probably related to the micromorphological characteristics of transitory intermediate weathering phases and, therefore, ultimately determined by the nature of parent rock mineralogy.

This mechanism determining kaolinite micromorphology in weathering environments is probably not unique to this example and may be a common weathering phenomenon. For example, in an investigation of several kaolinitic soils in the Piedmont province from Virginia to Georgia, Sand (1956) noted that in all cases, K-feldspar initially altered to secondary mica (sericite) and plagioclase often initially altered to halloysite. He found that the basal planes of vermicular kaolinite platelets were oriented parallel to, and pseudomorphed secondary mica—a description reminiscent of Pevear and Nagy's (1993) "copy-cat" kaolinite model. One of Sand's (1956) major conclusions was that secondary mica is an essential intermediate weathering phase in the alteration of feldspar to kaolinite with vermicular forms being a common result.

In more recent work, Robertson and Eggleton (1991) found that the kaolinite microfabric produced by tropical weathering of a granite in Queensland, Australia, was influenced by precursor mineralogy similarly to that described earlier for the Manzanita Oxisol. They found that secondary kaolinite from the weathering of plagioclase was generally finer grained than that derived from sericite. In addition, coarse-grained kaolinite contained remnant platelets of the sericite precursor.

Sand (1956) also noted that kaolinite pseudomorphically replaced primary mica "books". This particular form of kaolinite is probably not an uncommon morphology in lateritic profiles. Kaolinized mica was identified in the lateritic Cretaceous Minnesota saprolites (Parham, 1970), and Singh and Gilkes (1991, 1993) found that kaolinite pseudomorphically replaced mica in two lateritic profiles in Western Australia.

<u>Pedogenic Cements</u>. The fluorescent cements (O-F and P-F) which saturate areas of the kaolinite fabric, kaolinized micas, and occur as coatings around micropeds, appear to be related to the enrichment of Si relative to Al as indicated by EDX analyses. Although the composition of amorphous inorganic soil colloids can be quite variable (MacKenzie, 1975), two lines of evidence suggest that this amorphous material is largely silica. First, Singh and Gilkes (1993) found similar Si enrichments associated with amorphous silica cement distributed in the kaolinite matrix of a lateritic soil profile in Western Australia. They reported that these soil materials can contain significant quantities of amorphous silica (up to 20%) without a detectable XRD signature. Similarly, no XRD signature indicative of any amorphous phase including opal-A or allophane is apparent in the XRD analyses of Manzanita Oxisol material.

Second, several workers conducted analyses on the siliceous-rich kaolinite "polymorph" in the Ione Fm. which Allen (1928) originally dubbed "anauxite". Although he initially restricted this term to the large kaolinized mica books that occur both in source soils and Ione sediments, as the fine-grained massive kaolinite in Ione sediments is also siliceous-rich (Ross and Kerr, 1930), the term was gradually applied to all Ione kaolinite. Initially, "anauxite" was thought to have additional structural silica in a discrete silicate layer (Ross and Kerr, 1930). Analysis by Allen *et al.* (1969), Langston and Pask (1969), and Keller (1982) resulted in the unanimous conclusion that this "polymorph" is actually standard stoichiometric kaolinite but contains amorphous silica adhered to the surfaces of the kaolinite platelets. Based on these findings, Bailey and Langston (1969) suggested that the term "anauxite" should be officially dropped. Interestingly, Singh and Gilkes (1993) found the same range of Si enrichment in Si:Al ratios (EDX) in kaolinite from the Western Australian laterite (1.15–1.92) as Keller (1982) did in his analyses of amorphous silica enrichment in Ione kaolinite (1.21–1.89). Si:Al ratios in a few EDX analyses of silica-enriched kaolinite in the Manzanita Oxisol are 1.15–1.25.

Chamley (1989) noted that excess silica is a by-product of chemical weathering in which hydrolysis dissolves silicate minerals and kaolinite forms as an alteration product. The dissolved silica is then carried away as a component of the ground water leachate. The microfabric of the amorphous siliceous cement and the manner in which the cement coatings invaded the kaolinite fabric symmetrically on opposite sides of fissures and packing pores in Manzanita soil material suggests that the siliceous coatings precipitated from leachate solutions moving through the soil fabric.

<u>Potential for Kaolinitic Sediments and Criteria for Identification</u>. Soil scientists have long recognized that pedogenic cements including silica and iron oxides occur in a variety of soil types including warm-humid soils (Flach *et al.*, 1969). In addition, Flach *et al.* (1969) noted the ability of such pedogenic cements in soils to cement the clay fabric into sand- or silt-sized "hard, water stable, rock-like aggregates". The manner in which pedogenic cements including amorphous silica and iron oxides saturate and stabilize the kaolinite fabric in the Manzanita Oxisol has important implications for the ultimate stability of clay aggregates which could potentially be broken out of the Oxisol during erosion and transported in streams.

Singh and Gilkes (1993) found that amorphous silica imparts considerable induration to the kaolinite fabric in the lateritic paleosol in their study. In the Australian example, they reported that amorphous silica adsorbs to the 001 surfaces of the kaolinite platelets in the clay matrix and welds the clay particles together at their point of contact. They noted that the complete filling of the pore spaces between the clay particles is not required for silica to perform as an effective cement and amorphous silica in the amount of 5% or less can cement and stabilize the clay fabric in the soil matrix. Similarly, Langston and Pask (1969) found that amorphous silica performs as an effective cementing agent in kaolinite aggregates in Ione sediments and inhibits their disaggregation during sample preparation.

As demonstrated through this petrographic examination of the Manzanita paleosol, Oxisols have an inherent sandy nature resulting from their microped fabric (Stoops, 1983). The stability of the clay aggregates in this sandy soil fabric comes from a combination of the relative non-dispersibility of kaolinite, the nature of the pedogenic kaolinite aggregate microfabric, and additional cementing agents such as amorphous silica and iron oxides. These factors collectively point to the great potential of Oxisols to supply kaolinitic detritus to fluvial systems in the form of stable granular- or sand-sized clay aggregates upon their erosion.

Kaolinitic Oxisols are resistant to erosion (Soil Survey Staff, 1975) because of the inherent stability of kaolinite and pedogenic cements in the oxic horizon; however, the contact relationship between the Manzanita Oxisol and adjacent fluvial sediments (ie., buttress unconformity) suggests that significant incision and erosion of a thick section of the Oxisol occurred prior to the deposition of the Ione sediments deposited there (Figs. 7 and 8). If this was a regional phenomenon produced by base level fluctuations then kaolinitic soil debris should have been incorporated into Ione fluvial sediments in sufficient abundance to be detectable in petrographic analysis. The occurrence of significant quantities of pedogenic kaolinite in fluvial sediments could easily be mistaken for authigenic pore-filling kaolinite, especially since detrital kaolinite is not generally considered an important constituent in clastic sediments by sedimentologists.

The difficulty of distinguishing detrital pedogenic kaolinite from authigenic pore-filling kaolinite in sandstones is exacerbated by the occurrence of similar micromorphologies (ie., vermicular forms) in both cases. However, results of this petrographic investigation of the

Manzanita Oxisol indicate that pedogenic kaolinite possesses characteristic micromorphologies and it should be possible to differentiate between pedogenic and authigenic occurrences in sandstones.

The mineralogical and micromorphological features determined in this study to be characteristic of pedogenic kaolinite in addition to other associated pedogenic features collectively proved useful as criteria to evaluate the potential for the occurrence of detrital pedogenic kaolinite in the Ione fluvial system. These criteria are as follows:

1) Detrital pedogenic kaolinite aggregates should exhibit heterogeneous micromorphologies. In other words, kaolinite micromorphologies should be quite variable from grain to grain in terms of average particle size and arrangement. As kaolinite micromorphology is probably controlled by precursor mineralogy, this variability should be enhanced in streams eroding regions with variable lithologies. The variability should also be greater in high order steams (ie. those with many tributaries) and increase with distance of transport as the number of tributaries increases.

   The variable micromorphology of pedogenic kaolinite is an important feature which distinguishes it from diagenetic pore-filling kaolinite. The latter generally exhibits homogeneous micromorphologies and does not vary significantly from pore to pore over a small area of sandstone fabric. Wilson and Pittman (1977) suggested that monomineralic diagenetic clay assemblages occur as a result of specific physical and chemical burial conditions. Such conditions probably do not vary appreciably over a small region of fabric such as that encompassed by the area of a thin section. Photo 23 shows a typical example of authigenic kaolinite in a sandstone from the Pattani Basin, Gulf of Thailand.

   Post-depositional kaolinite replacement of argillaceous material in lithic sediments resulting from burial diagenesis could potentially be confused for an occurrence of pedogenic kaolinite. The other criteria listed here would need to be employed to resolve the origin of such an ambiguous occurrence.

2) Many detrital pedogenic kaolinite aggregates are likely to possess an aggregate microfabric characterized by larger kaolinite particles set in a matrix of smaller particles or colloidal material. This microfabric appears to be a fundamental characteristic of pedogenic kaolinite and probably enhances the stability of pedogenic clay aggregates for transport as bedload sediment. Diagenetic pore-filling kaolinite in sandstones typically lacks this heterogeneous aggregate microfabric (Photo 25; compare with Photo 9).

3) Detrital pedogenic kaolinite aggregates may be stabilized with amorphous siliceous cement. The occurrence of amorphous silica in pedogenic kaolinite may be manifested in a number of ways. In plane-polarized light, individual kaolinite aggregates containing this cement may appear pale. The kaolinite may also appear to have opaque coatings, clusters of fine-grained opaque particles, or a dusty appearance. These features associated with siliceous cement can be confused with iron oxide cement in transmitted light as they both appear opaque; however, in oblique white reflected light the two can be easily distinguished. Concentrations of amorphous silica cement exhibit a diffuse cream to pale yellow color as opposed to hematite and goethite which exhibit reddish and bright yellow colors, respectively. Amorphous silica cement complexed with organic matter will exhibit fluorescent yellow colors in blue reflected light and will appear to permeate the platelets and aggregates of clay.

4) Detrital pedogenic aggregates may be stabilized with iron oxide cement, either goethite or hematite. This cement may obscure the fine-grained clay fabric it saturates and, thus,

appear as massive iron oxide grains. Johnsson (1990) reported that clasts of this class of lateritic material are common in modern tropical sediments.

5) Detrital pedogenic kaolinite aggregates, especially those with coarse-grained kaolinite morphologies, may contain varying amounts of remnant sericite or other phyllosilicates such as smectite—intermediate weathering phases which may be recognized by higher birefringent colors. Remnant fragments of weatherable minerals such as feldspar may be present in the detrital kaolinite aggregate fabric and their presence is not necessarily indicative of post-depositional alteration.

6) Pedogenic kaolinite aggregates may incorporate minute crystals of TiO_2 (anatase/rutile) or monazite inherited from their granitic or metamorphic precursors.

7) Discrete sand-sized detrital kaolinite flakes possess pseudomorphic replacement "book" morphologies of their mica precursors. These large kaolinized mica grains may show signs of transport such as grain rounding and deformation by impinging resistant framework grains upon compaction. They may contain remnant precursor mica layers.

8) The evaluation of a potential occurrence of pedogenic kaolinite in clastic sediments using the criteria listed here should take into account possible modifications to the mineralogy and micromorphology of pedogenic clay aggregates by diagenetic processes. Potential modifications would include: 1) the deformation of kaolinite and precursor mineral morphologies with compaction; 2) the transformation of smectite to illitic clay phases (ie., $S \rightarrow I/S$); 3) the conversion of pedogenic amorphous siliceous cements to other forms of silica such as cristobalite and quartz as a result of either aging of the amorphous silica gels at ambient conditions or burial diagenesis; and 4) the remobilization of iron (Fe^{+3}) in detrital ferrugenous lateritic clasts (ie., hematite and goethite) and the precipitation of other iron cements (Fe^{+2}) in response to sediment burial under reducing conditions. The conversion of amorphous silica to other silica phases is discussed by Drees *et al.* (1989) and the diagenetic alteration of ferrugenous lateritic clasts and coatings is discussed in detail by Rude and Aller (1989).

A caveat should be considered when applying these specific criteria in the evaluation of detrital pedogenic kaolinite in sandstones. An occurrence of detrital kaolinite may not conform to all of the specific criteria listed here; however, taken collectively, these criteria along with the previously published general criteria for detrital clay listed earlier, should prove reliable to differentiate between an occurrence of detrital pedogenic kaolinite vs. authigenic kaolinite in sandstones.

Proximal Ione Fluvial Sediments

Lower Ione Deposits

Depositional Setting. The Ione Fm. fluvial deposits were formally subdivided into lower and upper members by Pask and Turner (1952) based on mineralogical differences that occur in both proximal and distal deposits noted by Allen (1929) and MacGinitie (1941). MacGinitie (1941) attributed the differences in composition between Lower and Upper Ione Member sediments to characteristics of the depositional setting under which they were deposited. Lower Ione sediments in proximal areas were further informally subdivided into the lower "channel gravels" and upper "bench gravels" (Figs. 3 and 10) by MacGinitie (1941) based on channel configuration and

Andesitic Series 90-200 m	Andesite breccia, mudflows and fluvial gravels. Probably correlates with the Mehrten Fm. (Miocene)
Rhyolitic Series 65 m+	Tuffs and intervolcanic channel sediments composed of gravels, sands and clays. Massive basal conglomerate locally occurs (6 m thick). Unit probably correlates with the Valley Springs Fm. (Oligocene-Miocene)
Upper Ione Sandstones 30 m+	Cross-bedded sandstones with abundant fresh feldspar and biotite.
Lower Ione Bench Gravels ("Red Gravels") 60-120 m	Compositionally mature sandstones and conglomeratic sandstones with interbedded clay lenses. Sediments oxidized and light colored.
Lower Ione Channel Gravels ("Blue Gravels") 10-40 m	Compositionally immature sandstones and conglomeratic sandstones. Cobbles composed of igneous and metamorphic bedrock materials. Sediments generally unoxidized and dark colored.
Basement Rocks	Paleozoic to Mesozoic metamorphics and Cretaceous intrusive igneous rocks.

Figure 10

Composite lithologic section of Tertiary rocks in the Nevada City area (after MacGinitie, 1941; Yeend, 1974).

sediment composition. He reported that the lower "channel gravels" ("deep gravels" of Lindgren, 1911) were deposited in a "V"-shaped valley (Fig. 3) during an initial "erosive stage" produced by a major base level lowering event. He noted that fresh bedrock material, scoured from the channel bottom during this channel cutting episode, accounted for the compositional immaturity of the "channel" sediments. These sediments generally appear dark because unweathered basement rock constituents were preserved in the reduced state below the water table (MacGinitie, 1941; Yeend, 1974). These authors also noted that the abundance of the dark blue and green metamorphic rock fragments in the sediments led the early gold miners to dub these the "blue gravels". The highest concentrations of gold occur in these lower channel gravels (Yeend, 1974). The early geologic investigators perpetuated the use of the term "gravels" to refer to the proximal Ione fluvial deposits. However, in addition to conglomeratic sandstones ("gravels"), the proximal Ione deposits are composed of sandstones and interbedded mudstones with finer sandy sediments dominating the upper beds (Yeend, 1974).

MacGinitie (1941) held that the Lower Ione "bench" gravels were deposited during the "aggradation stage" when the Ione streams back-filled the V-shaped channels and spilled onto the surrounding low-relief topography in response to a rise of the base level (Fig. 3). He showed that the Lower Ione bench gravels were deposited in shallow braided streams on a wide floodplain (Fig. 3). The bench sediments are compositionally mature with high quartz to feldspar ratios and significant amounts of kaolinitic clay. The bench sediments were subjected to surface weathering on the floodplain and appear "rusty" and comparatively light colored because of oxidation. As these bench sediments correlate with the Lower Ione sediments exposed in the Ione area (MacGinitie, 1941; Pask and Turner, 1952), they are the unit of primary interest in this study. All of the samples of proximal Lower Ione sandstones came from exposures in abandoned hydraulic mining pits which worked the fluvial deposits for placer gold.

Mineralogy. Petrographic and XRD analyses were performed on samples of proximal Ione fluvial sediments from various channels of the ancestral Yuba River to determine mineralogy. Results of XRD analysis on the <2 μm fraction of proximal Ione sediments are tabulated in Table 2. Sandstones sampled at Quaker Hill (#91-27B), Washington (#92-27), and Gold Run (#91-12) were probably deposited in high order channels (Fig. 4). Results of XRD analysis of the clay size fraction (<2 μm) shows that these Ione sandstones are characterized by clay mineral assemblages dominated by kaolinite. Variations in the minor clay constituents occur in the sediments from the different channels.

Petrographic analysis of three sandstones sampled from Gold Run, Quaker Hill, and Washington shows that these sediments are largely composed of quartz and kaolinite with trace to moderate amounts of feldspar (Appendix D). Kaolinite forms the matrix (pseudomatrix) of the sandstones and constitutes 40–49% of the sediment by volume. Feldspar occurs in greater abundance in the sandstone from Quaker Hill (#91-27B) with K-feldspar and plagioclase constituting 14% of the sediment. The quartz-kaolinite composition, lack of significant biotite, and the high quartz to feldspar ratio of these sandstones meet the mineralogical criteria of Pask and Turner (1952) to be classified as Lower Ione Member sediments.

In the sandstone sample from Quaker Hill (#91-27B), kaolinite is the dominant clay mineral constituting 85–90% of the clay assemblage with smectite and mica comprising the remainder (Table 1; XRD 7). Sandstone exposed in the hydraulic mine workings at Gold Run (#91-12) possesses a similar clay assemblage but with the additional component of halloysite (Table 1; XRD 9). The sandstone sampled near Washington (#92-27) differs in that vermiculite and gibbsite occur in the clay assemblage but little or no smectite occurs (Table 1; XRD 8).

The variability observed in the clay mineral assemblages of proximal Ione sandstones would have been influenced by factors such as the mineralogy of the bedrock in source areas and the modification of precursor source rock mineralogy by chemical weathering under the warm-humid Early Tertiary climate. The modification of the sediment clay composition by post-depositional chemical weathering should also be considered.

TABLE 2
Clay Mineral Abundance in the Clay Size Fraction (<2 μm)
of Proximal Ione Sandstones Determined by XRD

Sample ID	Location	XRD # (Appdx B)	Kaol %	Smec %	Mica %	Halloy %	Verm %	Other Minerals
91-31	Manzanita	10		25	5	70		Q
92-28	Manzanita	11		20	10	70		
92-30	Manzanita	6	75	20	5			Q
91-12	Gold Run	9	70	5	10	15		Q
92-27	Washington	8	85		10		5	Gb,Q,L
91-27B	Quaker Hill	7	85	5	10			
91-27A	Quaker Hill	13	15	80	5			
91-25	Scotts Flat	14	15	80	5			
91-26	Scotts Flat	12	45	45	10			

Other symbols: Gb = gibbsite, L = lepidocrocite, Q = quartz.

An examination of the clay mineralogy of the Ione fluvial sediments overlying the Oxisol at the Manzanita mining pit illustrates the influence of local source materials on the variability of sediment clay mineralogy. Clark (1965) and Yeend (1972) mapped the channel flowing through the Manzanita site as a low order stream flowing east towards the main channel of the ancestral Yuba River (Fig. 4). Cobble imbrication in conglomeratic sandstones at the Library site indicates an eastward flow direction supporting their interpretation. Consequently, this Yuba River tributary was carrying sediment derived from the local area west of Nevada City.

A 3 meter section of weathered, medium- to coarse-grained quartzose sandstone unconformably overlies the Oxisol at the at the Manzanita Library site (Cross-section A–A', Fig. 7). From visual inspection, the sediments do not appear to contain appreciable pore-filling clay and no sedimentary structures are apparent. Petrographic analysis shows that the sediment is composed of little more than quartz and clay (#92-30, Appendix D). XRD analysis shows that the clay mineral assemblage is composed of approximately 85% kaolinite, 15% smectite, and a trace of mica (XRD 6). These stream sediments were probably eroded from a combination of kaolinitic oxic and saprolite materials in nearby Oxisol exposures. The clay matrix composition of this Ione sandstone is similar to the clay assemblage of a nearby exposure of Oxisol saprolite material (#94-06, XRD 5) located 150–200 meters west of the Library site (Fig. 6) suggesting that the smectite component of this sediment was derived from Oxisol saprolitic material.

Overlying the quartzose kaolinitic sandstone unit is a 5 meter section of horizontally-bedded, matrix-supported conglomeratic sandstones (Fig. 7). Conglomeratic sediments of similar appearance back-filled a channel that incised the Oxisol adjacent to the Library (Cross-section B–B', Fig. 8). These coarser sediments have a much different sand and clay composition than the kaolinitic sandstones directly overlying the Oxisol. Petrographic analysis of three interbedded medium-grained sandstones in the conglomeratic section (Fig. 8) shows that these coarser sediments contain a large amount of clay (34–56%) and up to 18% feldspar with minor amounts of mica and rock fragments (#'s 90-23, 91-31, 92-28, Appendix D). In addition, the conglomeratic sediments possess a clay mineral assemblage composed of poorly crystalline smectite and halloysite with little or no kaolinite (#91-31, XRD 10). A similar sand and clay composition comprises the conglomeratic sandstones (#94-05) overlying both the Oxisol and the kaolinitic sandstones (Fig. 7).

Many of the rounded cobble clasts in the conglomeratic sandstones are comprised of partially to severely weathered granitic and metamorphic rock fragments (saprolite rip-ups). The association of severely altered lithic cobbles with relatively unaltered feldspar grains in the sandstone matrix indicates that the lithic gravel clasts were largely altered in the soil profile prior to erosion and transport. Although the soils in the local source area from which these smectitic/halloysitic sediments originated have long since eroded away, an examination of the lithology and mineralogy of some of these weathered rock fragments can offer insight as to the nature of both the precursor bedrock mineralogy and the soil type of the source area.

XRD analysis shows that the gravel cobbles possess a smectite/halloysite clay assemblage similar to the sandstone matrix composition but with additional minerals representing remnants of original precursor mineralogies. Analysis of one such dark-colored cobble shows the additional presence of abundant amphibole. Another cobble exhibiting foliation additionally contains mica and vermiculite. A granitic rock fragment contains abundant quartz and K-feldspar in addition to the smectite/halloysite clay assemblage. Thus, in addition to local granitic rocks, this stream was apparently eroding local amphibolite and micaceous metamorphic rock terrains reported to occur in the area (MacGinitie, 1941).

The smectite/halloysite clay assemblage of the sandstone matrix, the abundance of weathered rock fragments (saprolite rip-ups) with a similar clay assemblage, and the near absence of kaolinite collectively indicate that the channel was eroding an area that was covered by soils with a much different mineralogy than the kaolinitic soil horizons characteristic of the local Oxisol. A number of explanations could account for the drastic change in the clay mineralogy from the lower kaolinitic Ione sediments to the smectitic/halloysitic sediments above. One possibility is that the stream was eroding a local area in which weathering conditions were unfavorable for the development of kaolinitic Oxisols. Buol *et al.* (1980) pointed out that in modern intertropical areas Oxisols do not cover the entire landscape and that local topographic or drainage conditions may favor the development of other soil types such as Ultisols, Inceptisols, Alfisols, and Vertisols. While Oxisols are favored to develop on flat well drained areas under a tropical climate with alternating wet and dry periods, Buol *et al.* (1980) noted that other soil types occur on steep hillside slopes, and smectitic Vertisols may form in depressional landscapes with poor drainage under the same climatic conditions. The development of smectite is favored and preserved in Vertisols because of the greater amount of cations such as Mg, Ca, and Si available in the soil profile.

Another explanation is that a change in the climate led to the development of different soils with different clay mineral assemblages. A significant climatic change was postulated by MacGinitie (1941) as one explanation to account for the immature Upper Ione fluvial sediments. Miller (1991) showed that a drastic tempering of the global climate occurred beginning in the middle Eocene. By late Eocene time the global climate was significantly cooler (Frakes *et al.*, 1992). These smectitic-halloysitic sediments could represent weathered detritus developed under a different climatic regime after the local kaolinitic Oxisol materials were removed by erosion.

A third scenario is probably the most plausible. The contact relationship (ie., buttress unconformity) between the conglomeratic sandstones and the adjacent Oxisol at the Library site (Cross-section B–B', Fig. 8) indicates that significant incision and downcutting through the underlying Oxisol occurred prior to the deposition of these smectitic/halloysitic sediments. This erosional event may have stripped away the upper kaolinitic horizons of Oxisols that mantled the local source area leaving only partially weathered saprolitic material dominated by transitory clay phases (ie., smectite and halloysite) exposed at the surface. Chamley (1989) noted that although kaolinite is the dominant stable clay phase favored under a hot-wet climate, several other intermediate clay phases occur in the lower horizons of lateritic soils including mica (from feldspar sericitization), vermiculite, smectite, and mixed-layer clays. Allen and Hajek (1989) reported that halloysite derived from the alteration of feldspar is not uncommon in the saprolite below the pallid zone in many soil types including Oxisols. Although halloysite was not detected in the XRD analysis of the Manzanita profile, it is conceivable that halloysite occurs in the saprolite below the level currently exposed at the surface. The subsequent erosion of partially altered saprolite material would also explain the abundance of feldspar and partially altered saprolite rip-up fragments comprising the gravel cobbles in these sediments. Another major occurrence of smectitic/halloysitic clay assemblages is in soils developed from volcanic ash (Allen and Hajek, 1989; Chamley, 1989). However, extrusive volcanism did not commence in this region until the late Eocene at the earliest (MacGinitie, 1941; Yeend, 1974) and no volcanic material was observed in petrographic examination of these Ione sediments.

Irrespective of what specific mechanism produced the change in the clay composition of the sediments at the Manzanita site, it is clear that in tropical regions with widespread kaolinitic soils, the clay mineral composition of argillaceous detritus entering the regional fluvial system will vary depending on factors such as the local weathering conditions, local bedrock mineralogy, and the clay composition of the specific horizon of the local soil profiles that are being eroded. Therefore, the occurrence of clay minerals other than kaolinite such as vermiculite, halloysite, and gibbsite in the high order fluvial deposits at Washington and Gold Run was probably merely a consequence of the specific weathering and erosional conditions in the source areas of local tributary streams.

Sediment Texture and Clay Micromorphology. Petrographic analysis shows that sandstones from high order Lower Ione fluvial deposits in the ancestral Yuba River system (Gold Run, Quaker Hill and Washington) are largely composed of quartz and kaolinite in the form of detrital sand-sized clay aggregates and kaolinized mica grains (Appendix D). Quartz grains are angular and range between lower medium and lower coarse grain sizes. Based on quartz grain size distribution, the sandstones from Quaker Hill and Washington are moderately sorted while the sandstone from Gold Run is moderately-well sorted. Detrital clay aggregates occur in a similar range of grain sizes but with the largest ones occurring in the upper coarse sand size range. Little or no disaggregated detrital mud is apparent in these sandstones.

Quartz and feldspar grains are largely in floating and point contact with one another indicating that these sediments were not significantly compacted following deposition. Consequently, primary porosity is preserved and some of the clay aggregates retain a detrital subspherical grain shape. However, most of the clay aggregates were deformed plastically (squashed) between impinging hard framework grains and formed pseudomatrix (Photo 22). Thus, grain shape is not a viable criteria for the recognition of detrital clay clasts even in relatively uncompacted sandstones. However, kaolinite occurring in the form of clay aggregates conforms to the criteria listed by Dickinson (1970) and Wilson and Pittman (1977) for detrital clay occurring in sandstones in the form of argillaceous lithic fragments. In addition, it also conforms to the specific criteria for the recognition of detrital pedogenic kaolinite listed earlier.

The microfabrics of adjacent kaolinite aggregates varies considerably—a feature which facilitates the recognition of otherwise indistinguishable deformed clay clasts of similar composition (Photo 22). Thus, the boundaries of adjacent deformed kaolinite clasts in contact with one another are often marked by an abrupt change in microfabric. The detrital pedogenic clay aggregates exhibit kaolinite micromorphologies that are semi-homogeneous within each clast, but are heterogeneous between adjacent clasts. Clay aggregate micromorphological variations range from massive fine-grained kaolinite with indistinguishable crystallites to coarse-grained kaolinite exhibiting stacks and vermicular morphologies.

Many of the clay clasts exhibit pedogenic features inherited from the source soils from which they were derived. Some possess O-F and P-F cemented zones and coatings similar to the characteristic morphologies of organo-siliceous cements which permeate kaolinite micropeds in the oxic and saprolite horizons of the Manzanita Oxisol (Photo 11). Variations in the morphologies and amounts of O-F and P-F cement in adjacent clay aggregates also assist in their recognition as discrete clay clasts. Many of the kaolinized mica grains in these sandstones are also saturated with O-F cement similar to those in the Manzanita Oxisol. The O-F cement features appearing in nearby or adjacent clay aggregates exhibit different morphologies and occur in different stages of development indicating a detrital origin.

Some of the clay aggregates contain remnants of precursor minerals such as feldspar—an occurrence similar to that described for weathered argillaceous clasts in modern tropical river sediments undergoing active transport (Johnsson, 1990).

The characteristics of the clay aggregates described here apply to all of the high order Lower Ione fluvial sediments examined from Gold Run, Quaker Hill and Washington; however, the Washington sandstone contains an additional clay aggregate variant with a foliated fabric. The individual fine clay particles in these foliated clasts are platy with a slightly higher birefringence. They have a preferred orientation which varies from planar to slightly wavy (slaty foliation). These foliated clay clasts are probably the source of the vermiculite detected in XRD analysis (XRD 8). These micaceous pedogenic clasts are probably derived from slate or phyllite saprolite sources. As the underlying bedrock at this location is serpentinite, the abundance of these foliated clay clasts in the sediment indicates that the steam system was eroding a local metamorphic terrain somewhere nearby.

Petrographic examination of smectitic/halloysitic sandstones at the Manzanita Library site (#90-23, #91-31) shows that a few detrital clay aggregates of kaolinite composition occur but not in sufficient abundance to be detectable in XRD analysis (XRD 10). It is unclear if the pedogenic clay aggregates in these sediments occur with monomineralic clay composition (ie., wholly smectite or halloysite) or as a mixed clay assemblage. Petrographic examination under low magnification shows that the microfabrics of the majority of the clay aggregates appear fine-grained with no discernible crystallites visible. However, high magnification inspection reveals that many of the clay aggregates have a discernible microfabric with some possessing an intertwined fibrous or web-shaped microfabric exhibiting white to yellow birefringent colors (XPL) indicative of smectite. Fragments of incompletely altered precursor minerals occur in many of the clay aggregates.

Although the smectitic/halloysitic conglomeratic sandstone beds are poorly sorted, the sampled interbedded sandstones are well sorted and medium-grained (Fig. 8). A considerable amount of disaggregated detrital mud occurs in these low order stream sediments (Appendix D) suggesting that they were deposited under a less energetic flow regime compared to the high order fluvial sediments from Gold Run, Quaker Hill and Washington. For example, detrital mud comprises 45% of the sediment by volume of sample #90-23 resulting in a matrix supported arrangement of quartz, feldspar, and clay aggregate grains. The extremely fine-grained, massive, and homogenized fabric of detrital mud distinguishes it from clay aggregates which largely retain their subspherical detrital shape and possess discernible microfabrics with many retaining remnant saprolitic microstructure and precursor mineral fragments. The random particle arrangement of clay in the detrital mud with its consequent black (isotropic) birefringence (XPL) also distinguishes it from detrital clay aggregates exhibiting higher birefringent colors.

Sedimentology. The textural characteristics of the sediments from the high order Lower Ione fluvial deposits including the apparent absence of disaggregated detrital mud, coarse grain size, and moderate sorting collectively suggest an energetic flow regime at the time of deposition.

Quartz grains are denser than detrital clay aggregates because of the inherent microporosity of the latter. In the high order Lower Ione fluvial sediments, the largest quartz grains occur in the lower coarse sand size range while the largest detrital clay aggregates occur in the upper coarse sand size range. This size relationship suggests that these two constituents of differing densities in their coarsest grain size range were hydrodynamically equivalent. This relationship is especially apparent in the moderately-well sorted sandstone from Gold Run (#91-12) in which clay clasts attain grain sizes approximately 1.0 ϕ larger than quartz.

Post Depositional Weathering

The results of XRD analysis show that the matrix clay assemblages of proximal Ione sediments is similar to clay assemblages in local soil profiles. This poses other questions—were Ione sediments weathered *in situ* during temporary storage on Eocene floodplains? ...and did such weathering significantly alter the composition of the Ione sediments as with regional soils? MacGinitie (1941) reported that post-depositional weathering of Lower Ione bench sediments did affect the composition of the sediments. Indeed, evidence of post-depositional weathering can be seen in various exposures of proximal Lower Ione fluvial deposits in the form of iron oxide staining. However, "looks can be deceiving". Schwertmann and Taylor (1989) noted that hematite cement has strong pigmenting capability and only trace amounts will cause significant red coloration in outcrop. Therefore, the coloration of the outcrop produced by iron oxide cement should not be relied upon as an indicator of other weathering processes. The true severity of post-depositional weathering and its effect on sediment mineralogy can only be accurately assessed through microscopic examination.

In the course of this petrographic study, all the proximal Ione sandstone samples were inspected for signs and effects of post-depositional weathering. Some alteration features in the sediments potentially have a confused genetic interpretation with the possibility of either a detrital or *in situ* weathering origin. The following criterion was used to distinguish between ambiguous genetic possibilities: an alteration feature that is isolated and randomly arranged relative to other similar occurrences in the sediment suggests a detrital origin. Occurrences uniformly affecting a region of fabric with the particular feature occurring in the same stage of development indicates *in situ* weathering (authigenic occurrence).

Low Order Fluvial Sediments. The smectitic-halloysitic sediments adjacent to the Manzanita Oxisol do not display overt signs of post-depositional weathering except for a superimposed Holocene soil developed at the very top of the outcrop (Fig. 8). However, petrographic examination shows that these sediments show a wide range of weathering effects and micromorphologies. Beginning at the bottom of the section, the major alteration features apparent in sandstone sample #91-31 are iron oxide micronodules. The micronodules envelop corroded iron-bearing minerals that appear to be severely dissolved and oxidized to the degree that the original minerals are unrecognizable. In most cases, the iron oxide cement envelops adjacent sand grains. Most of the micronodules are approximately 1.0 mm in diameter—approximately 2–3 times the diameter of the dissolved mineral grains. Oxidation of the original mineral grains may have provided a nucleus for the precipitation of additional iron carried in solution in the ground water. These iron oxide features have the appearance of coarse sand-sized rust spots in outcrop. The red color of these micronodules (WRL) indicates that they are probably hematitic. In cases where heavy minerals are concentrated along cross-laminae, the micronodules are aligned along the cross-beds. This sample was taken from sediments exposed in a newly excavated construction trench. Consequently, there was probably insufficient time for these features to develop following recent exposure (Fig. 8). The same features can be seen in sediments at a similar stratigraphic level on the opposite side of the outcrop.

Not all weatherable iron-bearing minerals were similarly affected. A few amphibole grains that occur in the sediment exhibit no such signs of oxidation or dissolution. Apparently the only minerals affected were those at the highest position of the weathering stability series (Goldish, 1938) with the greatest vulnerability to weathering such as olivine and pyroxene. Most of the feldspar grains are angular and many show signs of incipient weathering and dissolution but not to the degree that would have prevented them from being transported in such a state. Skeletal grain remnants that would unequivocally indicate post-depositional dissolution of the feldspar grains do not occur.

Many detrital clay aggregates contain O-F and P-F cement features; however, as most of the clay clasts exhibiting these features are randomly dispersed in the sediment and the cement features exhibit dissimilar stages in development, a detrital origin is suggested. In addition, O-F cement permeates some of the feldspar grains. These affected feldspar grains show signs of partial dissolution. As there are no indications that the O-F cement was introduced into the sediment in this horizon following deposition, the O-F cements probably impregnated the feldspar grains in their source soils prior to erosion and transport.

A few meters higher in the section, post-depositional weathering affected the mud matrix of sandstone sample #90-23 (Fig. 8) with the development of two notable pedogenic features. First, packing voids occur in selected areas of the mud matrix. These range in appearance between accommodated packing voids to small unaccommodated vughs.

The second important feature is the invasion of O-F cement coatings into the mud matrix symmetrically on both sides of the packing voids (Photo 19). It is important to note that the O-F cement coatings do not occur in zones of mud matrix which lack packing void development. The O-F coatings fluoresce a yellow color in blue reflected light and exhibit a diffuse pale yellow color with oblique white reflected light. Some of the O-F cement coatings form three dimensional enclosures as indicated by the red interiors which soaked up plagioclase stain. In their most advanced stage of development, the packing voids form a network which segregates angular micropeds.

The occurrence, morphology, and petrographic attributes of O-F cement features in the clay matrix of this sandstone are similar to O-F cement coatings which permeate the clay fabric and micropeds in the oxic horizon of the adjacent Oxisol. Similar to their development in the oxic horizon, these O-F cement coatings attained the same degree of development over a small region of sandstone fabric indicating *in situ* formation resulting from pedogenic processes.

O-F cement also permeates fractures in feldspar and quartz grains. As the occurrence of O-F cement in the mud matrix in this sandstone can be attributed to *in situ* pedogenic processes, O-F cement may have infiltrated the fractures and dissolution voids in the framework grains simultaneously. Another possibility is that some of the quartz and feldspar grains may have inherited the pedogenic cements from their source soils and the presence of these cements may have helped to stabilize these partially dissolved and fractured grains enabling them to be transported as bedload sediment without disintegrating. The detritus in these fluvial deposits is presumed to have been derived from a local sediment source and these partially weathered grains with O-F cement were probably transported only a short distance.

Hydrolysis and dissolution of minerals was apparently more advanced in this sandstone than in #91-31, lower in the section. Many K-feldspar grains show the effects of partial dissolution along cleavage (Photo 19). Plagioclase dissolved to a greater degree. Most plagioclase grains were nearly completely dissolved and only remnants remain in some pores. Other voids are occupied by partially dissolved/partially oxidized remnants of iron-bearing minerals. Their dissolution was accompanied by precipitation of iron oxide micronodules similar to those described earlier. Some of these micronodules are probably composed of goethite as indicated by bright yellow colors (WRL) while others appearing reddish brown probably contain hematite. Distinct grain-shaped (rounded) voids in the mud matrix allows the differentiation between framework grain dissolution pores and irregularly shaped packing voids and vughs (Photo 19). No authigenic clay precipitation is associated with the dissolved feldspar grains nor does any occur in any of the moldic secondary dissolution pores. In addition, no illuvial clay is apparent in the fabric of this sandstone.

The highest stratigraphic position sampled in this section (Fig. 8) is a moderately sorted, medium-grained sandstone (#92-28). The framework composition of this sediment is similar to sandstone #91-31 lower in the section (Appendix D). It contains no disaggregated detrital mud and no O-F cement coatings are apparent. However, some of the open pores contain a different pedogenic feature that the sandstones lower in the section lack—pore-lining illuvial clay coatings (aka, clay cutans, argillans, clay skins). This authigenic clay morphology is produced by colloidal clay particles settling out of suspension and forming well oriented coatings against the walls of the pores. Illuvial clay originates from the physical disaggregation of other clay morphologies in response to the passage of ground water through an adjacent soil horizon (zone of eluviation), probably higher in the soil profile. The clay particles are transported in suspension either vertically downward or horizontally (translocated) by ground water fluids to a horizon where they settle out of suspension (zone of illuviation). The fabric of clay in the pore-lining coatings is characterized by an oriented, parallel particle arrangement. The clay coatings exhibit a yellowish tan color (PPL) and have high birefringent colors with undulatory extinction (XPL). These latter petrographic attributes are the result of the oriented and concentric arrangement of clay particles in the coatings. The clay coatings also exhibit a diffuse pale yellow color with white reflected light.

XRD analysis shows that this sandstone (#92-28) possesses a similar smectite/halloysite clay assemblage as sample #91-31 at the bottom of the section and apparently no kaolinite formed as a result of sediment weathering (compare XRD 10 and 11). Presumably, the illuvial clay in this sandstone (#92-28) is also comprised of smectite and halloysite.

Numerous large open voids in the sandstone framework suggest that grain dissolution occurred to a greater degree than in underlying sandstones. However, the large amount of feldspar remaining and the smaller volume of clay aggregates occurring in this sandstone compared to those lower in the section (Appendix D) suggest that the dissolution pores were partially the product of detrital clay aggregate dissolution. It is probable that much of the illuvial clay in this sandstone was derived from the disaggregation of clay aggregates within this same horizon. No intact iron-bearing minerals such as amphibole occur suggesting that they were largely dissolved in this horizon. The effect of dissolution on feldspar is slightly more advanced in this sandstone compared to those lower in the section. Only trace amounts of plagioclase remain. Iron oxide micronodules occur in association with oxidized iron-bearing minerals. Iron oxide precipitation also selectively occurred along illuvial clay coatings.

The organo-siliceous cements forming O-F coatings in the matrix of the sandstone lower in the section (#90-23) may have originated in this or overlying horizons in the soil profile where advanced grain dissolution and the degradation of humus was contributing siliceous and humic acid solutions to the ground water.

In spite of the occurrence of numerous large dissolution pores, petrographic examination indicates that the original arrangement of framework grains is largely intact and that disruption or collapse of the sandstone fabric as a result of mechanical soil processes did not occur at this level of the weathering profile. The preservation of well defined cross-bedding in outcrop supports this conclusion.

Except for the iron oxide micronodules at the bottom of the section, the sandstones in this section of smectitic and halloysitic Ione sediments exposed adjacent to the Oxisol display no overt macroscopic signs of weathering in outcrop . In contrast, the kaolinitic sandstones directly overlying the Oxisol (Fig. 7) show obvious signs of post-depositional weathering in the form of subhorizontal Liesegang bands of iron oxide precipitation with variable red and yellow colors.

The sandstone immediately above the contact with the pallid zone of the underlying Oxisol is moderately sorted and coarse-grained (#92-30, Fig. 7). This sediment possesses a surprising degree of induration compared to the extremely friable smectitic and halloysitic sandstones in the exposure adjacent to the Oxisol (Fig. 8). Quartz and a few detrital clay aggregates are the only framework grains occurring. However, the clay aggregates do not contain discernible delicate crystalline kaolinite morphologies. The fabric of these clay aggregates is similar to that of the homogenized oxic materials. This suggests that these clay aggregates were ripped up from the immediately underlying or nearby oxic horizons.

Sand grains are mostly in point contact producing substantial intergranular porosity with an open grain packing fabric (Photo 20). Some pores appear to be over-sized and may be dissolution voids; however, no grain remnants or crystalline clay morphologies occur within them. Illuvial clay forming pore-lining coatings is a major pedogenic feature occurring in these kaolinitic sediments. Pore-lining clay coatings are more abundant compared to the sandstone described earlier (#92-28) and line nearly the entire perimeter of open pores. As illuvial clay is the dominant occurrence of clay in this sediment (Appendix D), this clay is apparently kaolinitic (XRD 6).

The kaolinitic illuvial clay coatings possess similar petrographic attributes as those previously described for sample #92-28. Petrographic examination shows that the iron oxide coloration in outcrop originates from the selective precipitation of iron oxide cement on the illuvial clay coatings (Photo 20). The iron oxide cement has no other apparent occurrence. The iron oxide cement is reddish-orange in white reflected light and may be a combination of goethite and hematite.

Pore-lining illuvial clay is the only apparent form of cement in this sandstone fabric; however, the extraordinary induration possessed by this sediment may not be produced by the illuvial clay and sporadic iron oxide cements alone. Analysis of amorphous siliceous cement impregnating kaolinite in the oxic horizon of the underlying Oxisol shows that trace amounts of iron is associated with the silica. The iron is probably chelated with organic material complexed in the organo-siliceous cements. In this kaolinitic sandstone (#92-30), iron oxide cement only occurs in association with the clay coatings. This close association suggests that organo-siliceous cement may also be associated with the illuvial clay. If so, the oxidation of organo-siliceous cement adhered to the clay particles causing the release of chelated iron could explain why iron oxide cement is restricted to the clay coatings. Cementation of this sandstone fabric by clay coatings could be enhanced by amorphous silica adhered to illuvial clay particles. This silica cement may be what imparts the pale yellow color to the illuvial clay coatings in white reflected light.

The kaolinitic sediment substrate sampled higher in the weathering profile is a poorly sorted, medium- to coarse-grained sandstone with quartz comprising nearly 100% of the framework grains (#92-29; Fig. 7). Trace amounts of K-feldspar fragments occur. All other weatherable minerals were either dissolved or were never present in the original sediment.

Petrographic examination indicates that the sandstone fabric appears to have collapsed, probably as the result of mechanical processes associated with rooting and soil faunal activity. No vestiges of sedimentary structures are visible in outcrop. The sediment packing arrangement is different than in sandstone #92-30 lower in the section. In this upper horizon, sand grains are close-packed with fine sand filling the interstices between the coarser grains.

This sandstone has a kaolinitic clay mineral assemblage similar to underlying sample #92-30. Similarly, most of the clay occurring in this sandstone is in the form of illuvial clay with detrital clay aggregates occurring in trace amounts. However, many of the clay coatings appear to be fragmented and reoriented, probably as a result of mechanical soil processes. These illuvial clay fragments fill the interstices between the coarser sand grains. Fewer intact pore-lining clay coatings occur compared to the underlying sediment (#92-30). Consequently, this sandstone is not as well cemented as sample #92-30. The pore-lining clay exhibits a similar pale yellow color in white reflected light. Iron oxide cement occurs but only in association with the clay coatings. Again, no other pore-filling authigenic clay morphologies occur.

The only recognizable kaolinite morphology in this sandstone is in the form of a few detrital kaolinized mica books. The corners of these coarse-grained kaolinite grains are rounded probably as a result of abrasion during sediment transport. The grains show no signs of dissolution. The fact that these grains not only survived sediment transport but also withstood subsequent mechanical churning in the post-depositional weathering environment is a testament to their unusual resilience.

The weathering features observed in these kaolinitic sediments probably characterize a soil horizon within a few meters of the paleosurface in which the mechanical action of rooting and soil fauna disrupted the fabric of the sedimentary substrate. In contrast, post-depositional weathering did not mechanically affect the overlying smectitic and halloysitic conglomeratic sandstones (#94-05, Fig. 7). In outcrop, horizontal bedding is distinct and petrographic inspection shows that the depositional fabric is undisturbed. In thin section, little grain dissolution is apparent in these overlying sediments. The major feature of weathering is the occurrence of O-F cement coatings that invaded much of the detrital mud matrix of the sediment. The O-F cement features possess similar petrographic attributes as those occurring in sample #90-23 described earlier.

Petrographic examination shows that weathering features in these conglomeratic sandstones were produced by a less severe weathering regime than that which affected the underlying kaolinitic sediments. These weathering relationships clearly show that the weathering of the kaolinitic sediments occurred prior to the deposition of the overlying conglomeratic sediments. This implies that significant weathering of Ione sediment was occurring contemporaneous with various episodes of Ione fluvial deposition.

Interpretation of the weathering sequence in conglomeratic sediments adjacent to the Oxisol (Fig. 8) is more difficult. A Holocene weathering profile (probably post-mining activity) is superimposed on the sediments at the top of exposure. Although the weathering features described above were probably produced by Early Tertiary weathering, the possibility exists that the effects of Holocene weathering are superimposed over the Early Tertiary weathering profile. Retallack (1983) pointed out the difficulty of interpreting weathering profiles in cases where the "A" horizon of one soil profile is superimposed with the "B" horizon of an overlying and subsequent soil profile.

Untangling the weathering sequence of these soil profiles and assigning the observed weathering features to either an Eocene or Holocene weathering event is not important to this study. The important thing to note is that the weathering features observed in the Ione sediments at the Manzanita site are indicative of weathering regimes that were less severe and of shorter duration than the weathering conditions under which the underlying Oxisol developed. In addition, the weathering features observed in lithic materials at the Manzanita site that characterize both deep chemical weathering in the Oxisol and the less severe post-depositional weathering of the overlying sediments can be used collectively as an index to gauge the importance of weathering (ie., intensity and duration) in Ione Fm. fluvial deposits in other areas.

High Order Fluvial Sediments. Some of the high order Ione fluvial deposits sampled in this study also show no obvious signs of post-depositional weathering. Examples include the sediments exposed at Gold Run and Quaker Hill (Fig. 4) which appear white to buff with only a slight yellowish cast in outcrop. However, exposures of Ione sediments at Washington exhibit prominent orange iron oxide staining in outcrop. The massive iron oxide coloration of the bedding could be construed to indicate that significant weathering of the sediments occurred. However, this is an example in which an assessment of the severity of post-depositional weathering based solely on macroscopic appearance could lead to an overestimation of the true degree of weathering.

Petrographic examination shows that the coloration of the Washington sediment (#92-27) in outcrop is produced by iron oxide cement occurring in continuous 1.0 mm wide subhorizontal bands spaced approximately 1–2 mm apart. These bands are planar in the third dimension. The iron oxide cement exhibits an orange color in white reflected light. The iron oxide cement is restricted to O-F cement which permeates many of the detrital clay aggregates in this sediment. Where kaolinized mica grains occur in the path of the iron oxide bands, the O-F cement saturating the kaolinite pseudomorphs is similarly oxidized. No iron oxide micronodules occur. Amphibole grains occurring in trace amounts retain rounded grain shapes and show no signs of dissolution or oxidation. Other rounded, opaque sand-sized grains exhibiting colors typical of hematite and goethite (WRL) and randomly distributed in the sediment are probably of detrital origin.

XRD analysis of the sediment from Washington (#92-27) shows that the iron oxide coloration in outcrop is produced by lepidocrocite cement (XRD 8). Lepidocrocite is a polymorph of goethite with an orange color and has widespread occurrence in soils forming mottles, bands and concretions (Schwertmann and Taylor, 1989). The morphology of lepidocrocite cement forming continuous subhorizontal planar bands roughly perpendicular to the face of the outcrop suggests that its distribution was controlled by paleogroundwater fluctuations and not the result of Holocene (post-mining) weathering.

Petrographic examination of the sandstones sampled at Gold Run and Quaker Hill shows that minor iron oxide cement, probably goethite, is similarly associated with O-F cement in some clay aggregates. This minor iron oxide cement probably gives the slight yellowish cast to the sediments in outcrop. Aside from the O-F cement association and the occurrence of detrital goethite and hematite grains, no other form of iron oxide cement is apparent in the high order proximal Ione fluvial sediments sampled at the Gold Run, Quaker Hill or Washington sites.

Detrital clay aggregates containing O-F and P-F cement features abound in the sandstones from Gold Run and Quaker Hill (Photo 22). However, the random distribution of such grains and the fact that these cement features occur with a variety of micromorphologies and in various stages of development makes a strong case for a detrital origin for the clay clasts and associated pedogenic features. In contrast, some pedogenic cement features occurring within clay clasts in the sediment at Washington are probably the result of post-depositional weathering processes. P-F cement coatings occur in many but not all of the pedogenic clay clasts. These coatings occur in the same stage of development in most instances—invading the clay fabric the same distance from pore spaces. In addition, similar P-F cement coatings invaded the clay fabric of a mud laminae both symmetrically and equidistant from fractures. As these P-F cement coatings have an occurrence and petrographic appearance similar to P-F features saturating the clay fabric and micropeds in the Manzanita Oxisol, these P-F features are probably the petrographic manifestation of organo-siliceous compounds that were transported in solution in the groundwater. These pedofeatures may be indicative of an overlying weathering horizon in which severe leaching of weatherable silicate minerals occurred.

Curiously, the P-F coatings only occur in clay aggregates possessing the foliated micaceous fabric. The platy clay particles in these foliated pedogenic aggregates are oriented in a parallel or planar manner which results in a tight packing arrangement with little microporosity. P-F coatings are absent from pedogenic clay clasts with loose particle arrangements and greater microporosity. The association of the P-F coatings solely with these "tight" clay aggregates supports the notion previously suggested, that P-F coatings are the petrographic manifestation of organo-siliceous cement that completely filled the interstices between clay particles and excluded blue epoxy from impregnating those zones. The other clay aggregates with greater microporosity may also contain this authigenic siliceous cement but in insufficient volume to have completely filled the interstices. Consequently, blue epoxy was able to invade the clay fabric with no apparent pale petrographic manifestation.

Weathering processes such as hydrolysis resulting in the dissolution of weatherable minerals would have had a much greater effect in modifying Ione sediment composition than merely the introduction of iron oxide and other pedogenic cements. The sediments from Gold Run, Quaker Hill and Washington exhibit a wide range of feldspar abundance (Appendix D). These differences were probably the result of post-depositional weathering of Ione sediments in alluvial storage on the floodplain.

The sandstone from Quaker Hill (#91-27B) contains the greatest abundance of feldspar (14%) of the three high order Lower Ione fluvial deposits sampled (Appendix D). Both plagioclase and K-feldspar occur with the latter slightly more abundant. The angularity of the feldspar grains and the apparent absence of skeletal grain remnants both suggest that feldspar grains in this sandstone were probably not significantly affected by post-depositional weathering processes. Amphibole occurs in trace amounts in this sandstone and these grains similarly exhibit no apparent dissolution or oxidation features.

K-feldspar and amphibole grains occur in trace amounts in the sandstone from Washington (#92-27). Both of these minerals occur only in the fine to very fine sand range. Most feldspar grains are in the form of angular fragments. The few amphibole grains identified exhibit no signs of dissolution nor oxidation.

In contrast, K-feldspar grains occurring in the sediment from Gold Run (#91-12B) exhibit definite signs of dissolution in the form of skeletal grain remnants. Other feldspar grains are angular and show no signs of dissolution. No clay is associated with the skeletal feldspar fragments and the pores within these leached feldspar grains are completely free of argillaceous debris. This indicates that the skeletal feldspar grains were probably discrete detrital clasts and not incompletely altered precursor remnants originally transported within pedogenic clay aggregate hosts.

The dissolved appearance of these skeletal feldspar grain remnants initially suggests that hydrolysis caused the dissolution of these grains following deposition. However, a couple of important observations indicate that the dissolution of these K-feldspar grains probably did not occur as the result of *in situ* weathering, but were transported, albeit a short distance, to their final place of deposition.

First, amphibole grains occurring in this sandstone exhibit no apparent effects of dissolution. Amphibole is more susceptible to hydrolysis and other weathering processes than K-feldspar (Goldish, 1938; Chamley, 1989). Consequently, if the feldspar grains had been leached by *in situ* weathering processes then at least some of the amphibole grains would show similar effects of dissolution...none do. Second, the feldspar fragments that display severe dissolution features largely occur in the lower medium to lower very fine sand size range (1.5–4.0ϕ) while those that exhibit little or no effects of dissolution mostly occur in the medium sand size range (1.0–2.0ϕ). This grain size relationship suggests that the skeletal K-feldspar grains may have been severely leached prior to transport to the degree that they were physically incompetent to withstand extended bedload transport and disintegrated into smaller clasts at some point prior to deposition. If true, then the delicate appearance of these skeletal feldspar remnants indicates that they probably originated from a point only a short distance upstream. In such a scenario, the dissolved feldspar grains may have been incorporated into the active fluvial sediment by the reworking of sediment from a previous cycle of deposition that had weathered while subaerially exposed on the floodplain. Indeed, if this Gold Run sediment had been reworked again by fluvial channel migration and incorporated into a subsequent cycle of sediment transport, the incompetent skeletal K-feldspar remnants would undoubtedly have completely disintegrated into very fine sand- and silt-sized particles.

MacGinitie's (1941) observations indicate that post-depositional weathering under the early Eocene warm-humid climate probably resulted in the leaching of weatherable minerals in Lower Ione bench sediments while in storage on the floodplain. While the relationships of the weatherable minerals in the Gold Run sediment provide circumstantial evidence that weathering of the Ione sediment exposed on the floodplain was of sufficient intensity and duration to dissolve weatherable minerals and alter the sediment composition, evidence from the weathering profiles developed on the Ione fluvial sediments exposed at the Manzanita site provide direct evidence that this process occurred.

The bedding of the Gold Run, Quaker Hill, and Washington fluvial deposits contains numerous cut and fill structures indicating that significant reworking of the sediments occurred. Subaerially exposed floodplain sediment which had undergone weathering to various degrees was probably continually reworked in this Ione floodplain setting. The incongruent assemblage of both fresh and severely dissolved weatherable minerals in the Gold Run sediment could be the result of this mechanism. While the severely dissolved K-feldspar grains may have been derived from the reworking of previously deposited sediment that had been altered by weathering, the feldspar and amphibole grains which appear fresh and relatively unaltered were probably transported directly from an unaltered bedrock source or perhaps reworked from unweathered sediment.

Although only occurring in trace amounts, amphibole is ubiquitous in Ione fluvial deposits as granitic intrusions are widespread throughout Sierran source areas. Amphibole has low stability when subjected to chemical weathering processes (high on the weathering stability series of Goldish; 1938). Amphibole common in Ione sediments has a cation composition that includes Na, Mg, Ca, and Fe (EDX 7) which places it close to hornblende in composition. This composition makes amphibole highly susceptible to hydrolysis (Chamley, 1989). In addition, the ferrous iron in the amphibole in Ione sediments makes it sensitive to oxidizing conditions. Thus, its weathering potential combined with its widespread occurrence in Ione sediments makes amphibole an ideal indicator mineral for gauging weathering processes.

Petrographic evidence indicates that while the effects of post-depositional weathering are apparent in the high order Lower Ione fluvial deposits from Gold Run, Quaker Hill, and Washington, the weathering regimes were not severe enough to dissolve or oxidize amphibole. However, weatherable minerals such as feldspar occur in only trace amounts in the sandstones from Gold Run and Washington while feldspar is more abundant in the sandstone from Quaker Hill (Appendix D). These inconsistencies may have also been the result of repetitive cycles of Ione sediment "deposition–weathering–reworking" which caused a gradual decrease in the weatherable mineral component of Ione sediment in the downstream direction. This mechanism probably accounts for the fact that feldspar in the Washington sediment only occurs in the finer sand fraction and none is hydraulically equivalent to quartz. The Quaker Hill sediment with its greater feldspar abundance was sampled from the middle of the floodplain which may have been the site of major fluvial channels (Fig. 4). Sediments in the major channels probably contained a greater abundance of weatherable minerals compared to minor channels on the fringes of the floodplain because of the continual influx of unaltered sediment from tributaries.

Upper Ione Deposits

A major change in the sediment composition distinguishes Lower from Upper Ione sediments (Fig. 10). Upper Ione sediments were reported to contain significant amounts of biotite and feldspar (MacGinitie, 1941; Pask and Turner, 1952). MacGinitie (1941) proposed that another base level lowering event with renewed downcutting or a significant change in the climatic/weathering regime could account for the striking change in the composition of Upper Ione sediments.

Mineralogy. Two sandstones sampled in the Quaker Hill (#91-27A) and Scotts Flat (#91-25) hydraulic mining pits have a sand and clay matrix composition which differs significantly from the high order Lower Ione channel deposits described earlier. Petrographic analysis of the sandstone from Scotts Flat (#91-25) shows the occurrence of abundant feldspar (16%) and mica (25%)—criteria of Pask and Turner (1952) to be classified as Upper Ione Member sediments. The sandstone from Quaker Hill (#91-27A) has a similar composition. In addition, the clay assemblage of these sandstones is comprised of approximately 80% smectite, 15% kaolinite, and 5% mica (Table 2; XRD 13 and 14). Two aspects of this clay assemblage set these Upper Ione sediments apart from those of the Lower Ione. First, smectite rather than kaolinite is the dominant clay phase in these Upper Ione sediments. Second, the smectite phase is unusually coarsely crystalline (ie., large crystallite sizes–large N) and produces a sharp XRD peak (XRD 13 and 14). Finely crystalline smectite (ie., small particle size) with broad XRD peaks is more typical of the pedogenic smectite observed both in the Manzanita Oxisol and in Lower Ione fluvial sediments (compare with XRD 5, 6, 7, 9 and 10).

The clay mineralogy of mudstone beds interbedded with Upper Ione sandstones at Scotts Flat tells a different story. The clay assemblage of a mudstone sample (#91-26) contains smectite and kaolinite in approximately a 1:1 ratio with mica comprising the remaining 5% (Table 2; XRD 12). This clay assemblage is somewhat intermediate between the clay assemblages of Lower Ione and Upper Ione sandstones; however, the major difference between this mudstone clay assemblage and that of the enveloping sandstones is the lack of coarsely crystalline smectite. The smectite in the mudstone exhibits a broader XRD peak more typical of Lower Ione sandstones and the saprolite of the Manzanita Oxisol (compare with XRD 5 and 7). This anomaly between the clay compositions of the Upper Ione mudstone and sandstones is discussed below.

Sediment Texture and Clay Micromorphology. Upper Ione sandstones from fluvial deposits at Quaker Hill and Scotts Flat are largely composed of quartz, feldspar, biotite, and detrital sand-sized pedogenic clay aggregates. Quartz and feldspar grains are angular and range between upper fine and lower coarse grain sizes. Based on quartz and feldspar grain size distribution, the sandstones are moderately sorted. Detrital clay aggregates occur in a similar range of grain sizes but with some occurring in the upper coarse sand size range similar to the high order Lower Ione sandstones. A trace amount of disaggregated detrital mud occurs in these sandstones.

Most quartz and feldspar grains are in floating or point contact with adjacent grains indicating that these sandstones were not significantly compacted following deposition. Thus, primary porosity was preserved and some of the clay aggregates retain a detrital subspherical grain shape. However, most of the clay aggregates were deformed plastically to varying degrees between impinging hard framework grains and formed pseudomatrix. Although clay aggregates in these Upper Ione sediments have the same occurrence as those in the Lower Ione sandstones, their composition appears to be completely different. No detrital clay clasts composed wholly of kaolinite were unequivocally identified in the petrographic examination of the Upper Ione sandstones. In addition, the detrital clay clasts occurring in the Upper Ione sandstones have a higher birefringence—gray to straw yellow colors in standard thickness thin sections (30 μm) verses gray to black for kaolinite (XPL). EDX analysis of some clay clasts shows a magnesium-rich smectite composition with traces of sulfur, barium, chlorine, and potassium (EDX 4). These smectitic clay aggregates also conform to the criteria of Dickinson (1970) and Wilson and Pittman (1977) for the recognition of detrital clay in sandstones.

Backscattered electron images show that many of the smectitic clay aggregates are saturated with a cement. The cement appears as marbling in the clay fabric with a higher signal response (brighter). EDX analysis shows that the cemented zones have higher Ba and S cation values suggesting barite cement. Although barite is not a major component of soils, it occurs in some modern acid and river terrace soils (Doner and Lynn, 1989).

Another factor related to the abundant biotite occurring in Upper Ione sandstones uniquely sets these sediments apart from the Lower Ione. Whereas kaolinized mica is diagnostic of Lower Ione sandstones, most mica grains in these Upper Ione sandstones are "smectitized". This smectite alteration imparts a bleached color to the mica grains in hand specimen and in outcrop. MacGinitie (1941) also noted the occurrence of the abundant bleached mica grains as a diagnostic feature of the feldspathic sands (Upper Ione) overlying the kaolinitic Ione sediments (Lower Ione). The altered mica grains occur randomly distributed in the sandstone but also concentrated along laminae. In standard thickness thin sections, these smectitized micas exhibit yellow to orange birefringent colors as opposed to the red to blue colors of remnant biotite layers (XPL). Although the mica "book" structure is largely preserved, the altered "mica" layers in the pseudomorphs appear granulated compared to the clear uninterrupted crystalline appearance of adjacent unaltered muscovite grains (PPL).

Backscattered electron images show that the smectitized portions of the micas have a lower signal response than remnant mica layers. EDX analysis indicates that the smectitized zones are depleted in Mg, K, and Fe, and enriched in Al, S, Cl, and Ba (EDX 6) compared to the biotite precursor (EDX 5). Some of the brighter layers in BSE images exhibit higher Ba and S peaks in EDX analysis and are apparently zones of higher concentrations of barite cement. Other zones altered to kaolinite.

Petrographic examination shows that the smectite crystallites in the altered mica grains are pseudo-platy and are arranged parallel to the precursor mica layers suggesting a "mica template" arrangement reminiscent of the "copy-cat" kaolinite model of Pevear and Nagy (1993). Pseudomorphic smectite after coarsely crystalline mica satisfactorily explains the unusually well crystalline smectite peaks in XRD analysis of these two Upper Ione sandstones (XRD 13 and 14).

The coarsely crystalline smectite that produces the sharp XRD peaks in the Upper Ione sandstone analysis (XRD 13 and 14) is absent in the XRD analysis of the Upper Ione mudstone (XRD 12). The mudstones are comprised of disaggregated clay particles derived from the suspended load of the fluvial sediment. Since smectite has higher layer charge and disperses into smaller particles, larger smectite particles derived from smectitized mica may have dispersed into smaller particles while in suspension. Thus, the dispersed smectite particles would have produced a diffraction pattern with broader basal peaks. Alternatively, disaggregated smectitized mica may not have been prevalent in the suspended sediment load and was of insufficient volume in the mudstones to be detectable in the XRD analysis. Smectitized mica may not have been a significant component of the disaggregated suspended clay if the smectitized mica grains in the coarse sediment were relatively stable and were not being disaggregated to any great degree in proximal areas of the river system.

Petrographic analysis shows that little or no detrital clay aggregates composed wholly of kaolinite occur in the Upper Ione sandstones examined from Scotts Flat and Quaker Hill; however, kaolinite constitutes up to 15% of the clay fraction of these sandstones (XRD 13 and 14). Backscattered images show that zones of kaolinite occurring in largely smectitized micas accounts for some of the kaolinite observed in XRD analysis. Additional kaolinite may be located in detrital clay aggregates with mixed clay assemblages.

In contrast, kaolinite constitutes approximately 45% of the <2 μm fraction of the Upper Ione mudstone from Scotts Flat (#91-26; XRD 12). Petrographic examination indicates that all clay occurring in this mudstone was derived from disaggregated suspended sediment as no sand-sized clay aggregates occur. The higher abundance of kaolinite in this mudstone may have resulted from the scouring of the underlying kaolinitic Lower Ione sediments during flooding episodes—times when large volumes of suspended clay sediment would have accumulated in overbank deposits and ultimately formed mudstones.

Discussion

Bedload Transport of Clay. The occurrence of abundant sand-sized detrital pedogenic clay clasts in both Lower and Upper Ione sediments indicates that a large volume of eroded soil material was transported as bedload sediment in Ione fluvial systems. Results of petrographic analysis also show that the detrital clay aggregates in these sediments are saturated with various cements inherited from the parent soil environment. These pedogenic cements probably added considerable stability to clay aggregate clasts and facilitated their transport as bedload sediment in Ione streams.

The erosion and transport of sand-sized pedogenic clay aggregates is not an uncommon occurrence in both modern and ancient fluvial systems. Erosion experiments on modern soils by Alberts *et al.* (1980) show that most of the clay removed by erosion is in the form of sand-sized clay aggregates and the amount of clay transported in this form actually increases with distance of transport as suspended clay flocculates or adsorbs onto larger aggregates during transport.

Rust and Nanson (1989) reported that some modern Australian mud-rich, low gradient braided rivers transport significant quantities of smectitic clay in the form of sand-sized pedogenic clay aggregates derived from soils exposed in the proximal reaches of the river systems. Their experiments show that the pedogenic clay aggregates maintain the stability inherited from the original soil environment. Consequently, the clay clasts are sufficiently durable to be transported as bedload sediment. They found that although the pedogenic clay aggregates become rounded during bedload transport, they are not significantly reduced in size and abraded clay becomes part of the suspended load. They concluded that clay aggregate stability during transport is primarily the result of the aggregate nature of the pedogenic clay fabric which inhibits the smectitic clay from dispersing in water. The authors listed iron oxides, organic substances, and other solutes as important pedogenic cements providing additional stability to the detrital clay clasts.

Rust and Nanson (1989) also noted examples of sand-sized pedogenic clay aggregates occurring in ancient river systems. They acknowledged the problem of recognizing pedogenic clay clasts that deform during compaction and become difficult to distinguish from authigenic clay. They also speculated that the transport of pedogenic aggregates of kaolinite could conceivably occur with the erosion of Oxisols because of the combination of the sandy Oxisol fabric comprised of micropeds (Stoops, 1983) and clay aggregate stabilization by iron oxide cements. Indeed, pedogenic kaolinitic clay clasts are more likely to survive fluvial transport than smectitic clay clasts because of the greater stability of kaolinite in water.

Johnsson (1990) showed that detrital pedogenic clay clasts derived from the erosion of lateritic soils are an important constituent of bedload sediment in modern tropical rivers. His petrographic studies show that pedogenic clay clasts in tropical river sediments are so thoroughly altered by pedogenic processes that identification of the precursor grain mineralogy is impossible. He referred to the highly altered detrital pedogenic clay clasts as "alterites" after Franzinelli and Potter (1983).

Johnsson (1990) placed alterites into two categories—ferrugenous and non-ferrugenous. The non-ferrugenous alterites are largely composed of common clay products of chemical weathering such as kaolinite, smectite, and sericite. He found that the ferrugenous varieties possess fabrics similar to iron oxide materials in modern lateritic soils and probably represent reworked stable lateritic material [ie., the oxic material in Oxisols]. He reported that remnants of incompletely altered precursor minerals occur in the fabric of some altered detrital clay grains. Stoops (1983) also noted that remnants of unstable feldspar and ferromagnesian minerals may be left isolated in completely altered clay material in the oxic horizon of Oxisols in cases where the unstable mineral fragments are sealed off from further hydrolysis by weathering rinds. Amorphous silica cement sealing zones of kaolinite fabric in the soil could produce the same result.

Johnsson (1990) pointed out that detrital clay aggregates (alterites) from tropical settings fall into a class of sediment which is generally undervalued by sedimentologists for its paleoenvironmental significance and such material is generally referred to as "unidentified lithic fragments" in cases where severe alteration obliterated original grain mineralogy and structure. However, the mineralogy and fabric of thoroughly altered clay clasts occurring in the sediment of tropical rivers clearly places their genetic origin in the chemical weathering environment of tropical soils of source areas. Johnsson (1990) also addressed the difficulty of identifying altered argillaceous clasts in sandstones in cases where compaction caused the plastic clay clasts to deform and take on the appearance of matrix clay [pseudomatrix].

<u>Weathering of Pedogenic Clay</u>. Results of the petrographic examination of the Ione fluvial deposits at Gold Run, Quaker Hill and Washington show that the effect of oxidation on detrital pedogenic kaolinite aggregates probably played a major role in determining the macroscopic appearance of the sediments in outcrop. Detrital pedogenic clay aggregates occurring in these sediments contain adsorbed amorphous silica cement largely acquired in the soil environment prior to transport. In the Manzanita Oxisol, trace amounts of iron are associated with the amorphous silica cements that saturate the kaolinite fabric. This iron is probably chelated in organic matter complexed with the siliceous compounds. Based on observations from the oxic horizon of the Manzanita Oxisol, it appears that the oxidation of iron associated with the amorphous silica probably played a role in the subsequent redistribution of iron oxide cements.

The association of iron oxide precipitation with O-F cement in detrital pedogenic clay clasts in Lower Ione sandstones suggests that adsorbed amorphous silica probably had a similar role in the distribution of iron oxides resulting from the weathering of Ione sediments. Chelated iron was probably released by the slow oxidation of the organic matter complexed in the organo-siliceous cements adhered to the pedogenic clay when the sediments were subaerially exposed on the floodplain. Petrographic evidence shows that iron oxide cement from this source is the major cause of the weathered appearance of the sediments in outcrop (ie., iron oxide coloration). The occurrence of iron oxide cement as a result of this process while iron bearing minerals such as amphibole remain unoxidized suggests that this oxidation process begins operating at the earliest stages of sediment weathering before other chemical weathering processes become dominant.

<u>Authigenic Kaolinite From Sediment Weathering</u>. Results of the petrographic examination of the Ione sediments at the Manzanita site show that pore-lining illuvial clay coatings are the only neoformed *in situ* clay morphology that resulted from post-depositional weathering. These clay coatings were created by the translocation of existing clay particles and not from authigenic clay precipitation. The depth of weathering in which these illuvial clay features formed was probably within a few meters of the paleo-ground surface. The turbulence caused by the flux of ground water through the sandstone fabric at this shallow depth during wet periods would probably have inhibited the precipitation of delicate crystalline clay morphologies in pores. Thus, in such a shallow weathering environment, pore-filling authigenic kaolinite does not form in the same manner that authigenic clay precipitates in sandstones during burial diagenesis.

In the soil environment, delicate crystalline kaolinite morphologies form as a result of chemical weathering in the deep weathering horizons of mature soil profiles—ones that require a long period of warm-humid climatic conditions and a stable continental setting to fully develop. These conditions probably existed at the time of the formation of the deeply weathered Manzanita Oxisol and other similar lateritic weathering profiles buried beneath Ione fluvial deposits. However, evidence indicates that these conditions did not exist at the time of the post-depositional weathering of Lower Ione and subsequent sediments. First, pore-lining illuvial clay coatings are a major feature of the weathering profiles developed on the Ione sediments at the Manzanita site. Illuvial clay coatings are typically scarce or absent in the upper horizons of Oxisols because of the intense mechanical soil processes (Soil Survey Staff, 1975; Buol, *et al.*, 1980; Stoops, 1983). Therefore, these sediment soil profiles must have been produced by either a less severe weathering regime or by a shorter period of weathering. Second, the episodic periods of down cutting and subsequent deposition signified by the sequences of Lower and Upper Ione sediments indicates that significant base level fluctuations occurred (MacGinitie, 1941). As the period between the early Eocene to Oligocene was a time of tectonic quiescence in the region of the ancestral Sierras (Bateman and Wahrhaftig, 1966), these fluctuations were probably in response to a series of major eustatic sea level lowstands that correlate with the time of Ione deposition (Haq *et al,* 1987). Consequently, the period of time during which the post-depositional weathering of these Ione sediments took place was not one of long term stability. Third, XRD analysis of Ione sediment (#92-28) subjected to weathering at the Manzanita site shows a similar smectite/halloysite clay assemblage as sediments lower in the section which exhibit little effects of weathering. Kaolinite was not formed in this sandstone as a consequence of weathering. Thus, the illuvial clay coatings in this sandstone (#92-28) were probably formed from the translocation of existing clay particles and not from the precipitation of additional clay. Further, no pore-filling authigenic kaolinite in association with feldspar dissolution was identified in any of the proximal Ione sandstones.

<u>Weathering vs. Sediment Compositional Maturity</u>. Some of the Lower Ione fluvial sediments in proximal areas of the ancestral Yuba River system contain moderate amounts of feldspar such as the deposits at Quaker Hill. Other Lower Ione deposits such as those at Gold Run and Washington contain a more mature sediment assemblage with feldspar only occurring in trace amounts. These latter deposits approach the compositional maturity of distal Lower Ione sandstone deposits at Ione discussed later (Appendix D).

Several workers reported that sediments in modern tropical river systems are similarly compositionally more mature at the mouth of the river systems than in proximal channels (Franzinelli and Potter, 1983; Johnsson and Meade, 1990; Johnsson *et al.*, 1991). For example, Johnsson *et al.* (1991) show that while the sediment composition of some proximal channels of the Orinoco River system is feldspathic, the sediments at the mouth of the river system are of quartz arenite composition. They attributed this compositional maturity of tropical river sediments in the distal reaches of the river to a sediment maturing process that operates in tropical river systems as a result of chemical weathering. They proposed that while the active river channel migrates to other parts of the floodplain, chemical weathering under the tropical climatic regime has sufficient time to alter the composition of sediments in long term alluvial storage on the floodplain. The dissolution of feldspar and other weatherable minerals leaves the floodplain sediments enriched in quartz. When subsequent fluvial activity reworks the weathered sediments, the reincorporated material is more quartzose than the sediment in the active fluvial channel with the ultimate effect being the dilution of the transported sediment by material of greater compositional maturity. As chemical weathering of sediments in alluvial storage and fluvial reworking operate simultaneously along the entire course of the river system, the river sediments approach a quartz arenite composition at the river mouth.

Johnsson *et al.* (1991) reported that the two crucial factors necessary for this tropical sediment maturation process to operate are: 1) a tropical climate and 2) sufficient time for chemical weathering to alter the sediments while in alluvial storage. Evidence indicates that both of these factors existed in proximal floodplain areas of Ione river systems during Lower Ione deposition. First, a tropical climate existed in the early Eocene during the period of Lower Ione deposition. Second, petrographic analysis of proximal Lower Ione sediments in the ancestral Yuba River system appears to support the mechanics of this compositional maturing process. For example, the sediments at Gold Run contains remnants of severely leached feldspar grains presumably derived from reworked fluvial sediments. Further, petrographic evidence from Ione sediments at the

Manzanita site indicates that regional post-depositional weathering was apparently of sufficient duration to cause the dissolution of weatherable minerals.

Additional evidence that this sediment maturation process operated in the Ione depositional system comes from observations of MacGinitie (1941). He reported that the Lower Ione bench deposits were formed by streams migrating across a wide floodplain (Fig 3) which resulted in a significant retardation of the transport of sediments to the basin. He believed that the thin-bedded, braided Lower Ione sediments sitting exposed on the wide floodplains in proximal areas were highly susceptible to surface weathering and that there was ample time for chemical weathering to leach out the weatherable minerals and alter sediment composition. Based on his observations of numerous outcrops of weathered Ione deposits that were completely leached of feldspar and other weatherable minerals, he concluded that the weathering of Lower Ione sediments while in alluvial storage on the floodplain was apparently a common occurrence.

The Lower Ione bench deposits in proximal areas are comprised of amalgamated sheet sandbodies with pervasive cut and fill structures implying that the Lower Ione floodplain sediments were probably continually reworked. MacGinitie (1941) also reported that the depositional setting of the proximal bench sediments probably favored the continual fluvial reworking of floodplain sediments. Thus, this tropical sediment maturing process operated in proximal Lower Ione river systems and was probably an important process in the formation of the mature mineral assemblage (ie., quartz-kaolinite) that occurs in some proximal Lower Ione floodplain deposits.

Climate Change. The middle Eocene marked a period of transition from global tropical conditions in the early Eocene to more moderate climatic conditions in the late Eocene (Frakes *et al*., 1992). This period of global cooling may have been initiated by a significant drop of global temperatures occurring at the early/middle Eocene boundary followed by another major drop at about the middle/late Eocene boundary (Miller, 1991). The transition from the kaolinitic clay assemblage typical of Lower Ione sandstones to the dominantly smectitic clay mineral assemblage of Upper Ione sandstones may have been, in part, a consequence of this dramatic climatic tempering. In addition, the occurrence of major amounts of feldspar in distal Upper Ione sandstone deposits reported by Allen (1929) and Pask and Turner (1952) indicates that a compositional maturing process was not operative on Upper Ione sediments. Apparently, the climate had changed sufficiently by Upper Ione time that the modification of the sediment composition as a result of post-depositional weathering of sediments on the floodplain was negligible.

Intervolcanic Fluvial Sediments

The results of the petrographic analysis of intervolcanic fluvial sediments are reported here as an additional example of detrital pedogenic clay occurring in fluvial systems.

The general criteria for the recognition of detrital clay aggregates in sandstones outlined earlier are ideally illustrated in clayey sediments of the intervolcanic fluvial deposits exposed at Baxter (Fig. 5). These intervolcanic fluvial sands lie stratigraphically above the Ione Fm. deposits and are separated from the Ione by a ~20+ meter section of volcanic tuffs (Figs. 3 and 10). Much of the sediment in the intervolcanic fluvial deposits is derived from the erosion of these underlying tuffs.

The tuff units are comprised of 15+ meters of air-fall ash deposits with abundant glass shards and an upper 5 meter fine ash layer with no shards. Petrographic examination shows that a lacustrine environment is indicated for this upper ash bed by the exclusion of all but the finest volcanic ash particles and the occurrence of abundant fresh water diatoms and sponge spicules. The age of this upper tuff based on microfossils was estimated to be late Eocene and no later than earliest Oligocene (Arends, 1992). These tuffs may correlate with other biotite-rich tuffs in this region of the Sierras dated at 37.8 Ma (Yeend, 1974).

The ash material in these tuff beds altered to finely crystalline smectite and halloysite (XRD 15). It is possible that this mineral assemblage is indicative of rapid burial and that there was only a short time interval available for the Eocene climatic regime to alter the amorphous materials. Alternatively, the smectite/halloysite mineralogy may be another indication that the local climate had cooled significantly by late Eocene time. Chamley (1989) reported that the rapid hydrolysis and alteration of the abundant amorphous material in ash deposits to smectite and halloysite is favored under a warm-temperate climate with dry periods. Further, he pointed out that the persistence of these minerals combined with the absence of kaolinite precludes the existence of a hot-wet tropical climate.

The fabric of the upper tuff bed exhibits features indicative of surface weathering. Petrographic examination indicates that packing voids and O-F cement coatings occur throughout the clay fabric. The O-F coatings invaded the clay fabric symmetrically on both sides of packing voids and many form subspherical enclosures in the ashy fabric. The O-F cement coatings have the same petrographic appearance as those in the oxic horizon of the Manzanita Oxisol and are probably composed of amorphous silica. Amorphous silica is reported to be a common by-product of the alteration of volcanic ash material in weathering profiles (Mitchell, 1975).

The overlying intervolcanic sediments are horizontally laminated sandstones with interbedded mudstones. The sandstones are characterized by intercalated fine- to coarse-grained laminae. The texture of these sands consists of a combination of "dense" framework grains comprised of quartz, plagioclase, biotite, volcanic rock fragments and glass shards, mixed with sand-sized detrital clay aggregates (#91-08, Appendix D). The dense framework grains in the coarser laminae are moderately sorted, medium-grained, and angular (Photo 21). In contrast, the clay aggregates are rounded with grain sizes ranging between coarse sand and granules—much larger than the modal grain size of the dense grains. The finer grained laminae exhibit a similar "bimodal" grain size distribution determined by clast composition. The fine- to medium-grained sands are well sorted with the dense framework grains and clay aggregates concentrated in the fine and medium sand fractions, respectively.

Two important aspects of the sedimentology of the detrital clay clasts are apparent through petrographic observations of these coarse and fine-grained laminae. Based on the degree of sorting, the denser framework grains in these sand laminae are hydrodynamically equivalent. The larger modal grain size of the detrital clay clasts with their inherent microporosity and lower density compared to the quartz and feldspar grains suggests that these constituents of differing densities were also hydrodynamically equivalent. Also, the ratio of detrital clay aggregates to dense framework grains is greater in the better sorted, finer grained sand laminae. This relationship suggests that sediment grain size and sorting were probably controlling factors that determined the abundance of detrital clay aggregates in these sediments. One possible explanation for this could be that the detrital clay clasts are more stable in the fine- to medium sand size range than in the coarse sand range.

Detrital volcanic smectite/halloysite clay aggregates derived from the scouring of the underlying tuff deposits are easily recognized by their distinctive fabric containing sponge spicules and diatoms (Photo 21). Also occurring, but in lower abundance, are detrital kaolinite aggregates of approximately the same size recognized by the familiar vermicular kaolinite micromorphologies contained within them. A detrital origin of the clay aggregates is indicated by the lack of any evidence of post-depositional weathering of the sediment such as dissolution of unstable framework grains or iron oxide precipitation. Glass shards which are very sensitive to alteration appear unaffected in petrographic and SEM images and were not altered to clay. In addition, SEM images show that delicate microscopic explosive froth patterns imprinted on their faces are preserved.

XRD analysis of the clay size fraction of this sandstone records the mixture of these two clay assemblages (XRD 16). In addition to the underlying tuff, the stream was obviously eroding an exposure of kaolinitic soil somewhere upstream. The clay mineralogy of this sandstone illustrates the principle that the clay mineral composition of fluvial sediments reflects the composition of the soils in the source areas being eroded (barring any diagenetic alteration).

Although this sandstone is not significantly compacted, thin section views show the effects of even slight compaction on the plastic detrital clay clasts. Many of the large volcanic clay aggregates were flattened into discoid shapes (Photo 21). In contrast, the kaolinite aggregates retain a subspherical shape but were deformed at their margins because of impinging adjacent hard framework grains. The manner in which the kaolinite aggregates were squeezed into interstices between adjacent framework grains demonstrates their plastic nature. In cases where individual kaolinite aggregates came to rest in contact with one another, they can be distinguished by variations in their microfabrics in both plane-polarized and cross-polarized light.

O-F and P-F cements occur in many of the volcanic clay aggregates (Photo 21). In blue reflected light, yellow fluorescent cement appears to permeate both the volcanic and kaolinite clay aggregates. The fluorescent nature suggests an organo-siliceous composition similar to amorphous pedogenic cements previously discussed. These cements probably enhanced the stability of the clay aggregates and facilitated their transport as bedload sediment.

Distal Ione Fluvial Sediments

Depositional Setting

The kaolinitic Ione sediments in the "type" area at Ione are comprised of well sorted sandstones, poorly sorted conglomeratic sandstones, and mudstones. The mudstones locally contain interbedded lignite up to a few meters thick. Sedimentary structures indicate that the well sorted, cross bedded sandstones were deposited in braided streams in a fluvial-deltaic environment with an east to west flow direction (Rodgers, 1986). Matrix supported conglomeratic Ione sediments occur at the top of the Ione section exposed in the Ione area and may represent a regional progradation of proximal alluvial fan facies over more distal braided fluvial facies. Allen (1929) reported that conglomeratic proximal fluvial sediments (auriferous) interfinger with finer grained braided fluvial sediments on the north side of Ione (Muletown). This interbedding relationship may represent a similar depositional setting to the alluvial fan/braided stream complex described for the Ione at its southern most occurrence near Fresno (Palmer, 1978).

The interbedded mudstones in the Ione area probably represent accumulations of disaggregated mud in depositional settings such as abandoned channels or fluvial overbank deposits filling interdistributary areas. This depositional scenario is supported by organic geochemical analysis performed by Stout (1993) of the UNOCAL Corp. on lignitic mudstones sampled from Lot 232 near Ione (Fig. 5). Using gas chromatography (GC) and gas chromatography–mass spectrometry (GCMS) analytical techniques, Stout (1993) reported that terrestrial biomarkers (land plants) dominate the extractable organic matter in the mudstone. Biomarkers are molecules derived from specific terrestrial or marine biological precursors. In addition, Stout found no evidence of a marine algal input to the mudstones. He also reported that the low organic (2.19% wt.) and pyritic (0.73% wt.) sulfur contents are consistent with a fresh water source. The results of the molecular and sulfur analyses collectively indicate that the mudstone deposits formed above the tidal range and beyond the influence of marine brackish waters. Stout (1993) concluded that all organic indicators point to a fresh water, swampy upper delta plain or fluvial environment of deposition for the lignites and associated mudstones.

Mineralogy

Sandstones. Samples from several deposits of Ione sediments in the Ione area representing a variety of depositional facies were analyzed to determine mineralogy using petrographic and XRD methods. XRD analysis of conglomeratic sandstones sampled at Lanes (#89-18) shows that the clay size fraction (<2 μm) is predominantly composed of kaolinite with a trace amount of mica (XRD 17). The clay assemblages of well sorted Ione sandstones from Apricum Hill (#89-09) and Jones Butte (#89-29) are similar to the conglomeratic sandstones at Lanes (XRD 17). This kaolinitic clay matrix composition appears to typify Lower Ione sediments in the Ione area as XRD patterns of sandstones exposed at the Old Sand Plant and the Owens-Illinois mine pit show similar clay assemblages.

Petrographic analyses of both the conglomeratic and well sorted sandstones show that these sediments are largely composed of quartz, kaolinite, and heavy minerals (Appendix D). Kaolinite forms the matrix of the sandstones (pseudomatrix) and constitutes 52–67% of the sediment by volume in five well sorted distal Ione sandstones examined petrographically (Appendix D). Weatherable minerals such as feldspar and amphibole occur in trace amounts. Amphibole grains occur both randomly dispersed in the sediment and in laminae concentrated with heavy minerals. The quartz-kaolinite composition of these Ione sandstones is indicative of Lower Ione Member sediments based on the mineralogical criteria of Pask and Turner (1952).

Gillam (1974) reported the occurrence of feldspathic sediments a few kilometers south of Ione matching the description of Upper Ione sandstones of Pask and Turner (1952); however, no Upper Ione sediments were encountered in this study in the Ione area. If Upper Ione sediments were originally present within the Ione area encompassed by this study, they were probably removed by Pleistocene erosion.

Mudstones. Petrographic examination shows that the Ione mudstones in the Ione area are composed of clay with trace to minor amounts of silt-sized quartz and other heavy minerals. XRD analysis shows that the Ione mudstones have a kaolinitic clay assemblage similar to the sandstones but with minor differences. XRD analysis of a mudstone at Jones Butte shows that it lacks the mica contained in the overlying sandstone (#89-29). Although mudstones in the Bacon pit and at Lanes (Fig. 5) are similarly kaolinitic, they contain trace amounts of smectitic clay phases. Mudstone sample "B6" from a position approximately 10 meters below the top of the Ione section in the Bacon pit is predominantly kaolinite but contains a trace amount of smectite (XRD 18). One meter above, sample "B5" contains trace amounts of mica plus two smectitic phases—smectite and regularly ordered (R1) interstratified illite/smectite (I/S) containing approximately 40% smectite layers. This is a similar clay assemblage as that of the mudstone exposed at Lanes (#89-16; XRD 19). It is not surprising to find smectite in the clay deposits derived from Sierran sources as streams were eroding saprolitic material with smectite components. The I/S component in some of these mudstones was probably clay scoured from some of the local argillaceous metamorphic bedrock sources over which the streams were traversing. For example, Allen (1929) reported that outcrops of white saprolite of the underlying Mesozoic slate occur at the eastern margin of the Ione deposits at Ione. Ione streams would have traversed these terrains immediately prior to entering the Ione basin. Alternatively, the I/S phase could be authigenic from the transformation of some of the smectite to illitic clay resulting from burial diagenesis. However, as these Lower Ione sediments were buried to a maximum of only a couple hundred meters, this latter scenario appears unlikely.

Above sample "B5" in the Bacon pit, mudstones gradually become more smectitic higher in the section such that the mudstone "M21" at the top of the Ione section in the Bacon pit contains approximately 25–30% smectite (XRD 21). The sharp, narrow peaks of the smectite in the XRD diffraction pattern indicates that it is comprised of large smectite crystallites similar to the smectite that pseudomorphed mica in the Upper Ione sandstones near Nevada City (compare with XRD 13 and 14). This coarsely crystalline smectite in the Bacon Pit mudstones is dissimilar to the finely crystalline smectite typical of saprolite material such as in the Manzanita Oxisol and other local soils (compare with XRD 5 and 10). A possible explanation for the occurrence of this coarsely crystalline smectite is offered below.

The abrupt appearance of smectite near the top of the Lower Ione mudstones is not restricted to the Ione area. A similar trend in Ione mudstone clay assemblages occurs in the Ione clay beds at Lincoln (Fig. 2). The lower beds in the Lincoln clay pits are comprised of nearly monomineralic kaolinite assemblages similar to those in the Bacon pit at Ione. At the top of the section, sample "Lincoln 6" contains up to 20% smectitic phases including smectite and mixed-layer illite/smectite (XRD 22). The smectite phase occurring in the Lincoln 6 mudstone is coarsely crystalline similar to that occurring in the M21 clay at Ione.

Kaolinite Micromorphology

Sandstones. The coarsest grained facies of non-conglomeratic Lower Ione sandstones occurs at the eastern edge of the Ione basin in an abandoned open pit mine at Apricum Hill (Fig. 5). The exposure at Apricum Hill is a 12 meter section of white, horizontally bedded, well sorted, medium- to coarse-grained sandstones. The sandstone section is topped by a paleosol described by Singer and Nkedi-Kizza (1980). In this same vicinity of the eastern margin of the Ione basin, an overlying sequence of poorly sorted conglomeratic sandstones is separated from the well sorted white sandstones and mudstones by an erosional contact. The conglomeratic sandstone at Lanes is representative of this facies. At Apricum Hill, only remnants of the overlying conglomeratic sediments remain in the form of a lag gravel of quartz cobbles which rests on the surface of the exhumed paleosol.

Sandstones in the Lower Ione section at Apricum Hill are largely composed of quartz, and detrital forms of kaolinite in the form of sand-sized pedogenic clay aggregates and kaolinized mica grains. The various micromorphologies of kaolinite occurring in these coarser sandstones are typical of the other well sorted sandstones in the Ione area examined in this study. Petrographic analysis of the coarsest-grained sandstone sampled (#89-10) indicates that kaolinite in various detrital forms constitutes approximately 65% of the sediment by volume (Appendix D). Quartz grains are angular and restricted to the medium sand fraction. This sandstone is well sorted based on the size distribution of quartz grains. In contrast, kaolinite aggregates and kaolinized mica grains are concentrated in the coarse sand fraction. The average diameter of the kaolinized mica books is 0.5–1.0 mm but some are as large as 2–3 mm in their longest dimension. The largest ones are concentrated along coarse-grained laminae.

In well sorted distal Ione sandstones, heavy minerals occur randomly dispersed in the sandstone fabric but mostly concentrated along laminae. They are hydrodynamically equivalent to quartz and feldspar grains. Consequently, the denser heavy minerals consistently occur in a slightly smaller modal grain size than quartz and feldspar (Photo 24). The coarse-grained kaolinized micas and kaolinite aggregates with inherent microporosity and an overall lower bulk density are hydrodynamically equivalent to the denser, medium-grained quartz grains (Photo 24 and 27). The combination of these sand constituents of differing densities resulted in a well sorted, bimodal sandstone (Criteria 1, above–Wilson and Pittman, 1977).

Most kaolinized mica books retain their original grain shape although some show deformation between impinging quartz grains. Most of these grains are rounded because of abrasion during bedload transport. The abundance of these large clay grains in distal sandstones indicates that they had sufficient integrity to withstand bedload transport in the Ione fluvial system. This is not surprising considering the apparent resistance of kaolinized mica books to the intense mechanical soil processes occurring in the zone of bioturbation in the Manzanita Oxisol (Photo 16). A few unaltered mica books and micaceous metamorphic rock fragments occur in the same size fraction as the kaolinized mica grains.

In contrast to the kaolinized mica grains, the detrital kaolinite aggregates were deformed by compaction and form pseudomatrix in distal Ione sandstones (Photos 24, 27 and 29). Few, if any, possess their original detrital subspherical grain shape. However, the detrital origin of the clay aggregates in these sandstones is unequivocal as it meets both the general criteria for the recognition of detrital clay in sandstones (Dickinson, 1970; Wilson and Pittman, 1977) as well as the specific criteria for detrital pedogenic kaolinite, both listed earlier. The clay aggregates were compressed between impinging quartz grains. Consequently, these clay clasts conform to the margins of adjacent rigid grains and were squeezed into the narrow openings between them (Photo 24) (Criteria 2 and 3, above–Dickinson, 1970; Wilson and Pittman, 1977).

Adjacent kaolinite aggregates can be distinguished by an abrupt change in microfabric at their boundaries (Photo 24, 27 and 29) (Criteria 5, above–Dickinson, 1970). The diversity of microfabrics possessed by the clay aggregates in these distal sandstones reflects the diversity of lithologies in source areas of the Ione fluvial system. These kaolinite microfabrics include extremely fine-grained massive kaolinite in which the individual clay particles are not visible, coarse-grained kaolinite forms with discernible crystallites, and very coarse-grained kaolinite particles with vermicular and micaceous habits (Photo 27). Clay aggregates with this latter morphology often contain remnant mica platelets. In addition, some clay aggregates contain partially dissolved remnants of other mineral precursors such as feldspar (Photo 29). BSE and EDX analyses show that minute, equant TiO_2 crystals also commonly occur dispersed in the fabric of clay aggregates.

O-F and P-F cements permeate kaolinized mica grains and kaolinite aggregates in a similar manner as in the kaolinite fabric of the Manzanita Oxisol. Allen *et al.* (1969) reported that amorphous silica occurs in kaolinized mica ("anauxite") in Ione sediments from the Ione area. The patterns of yellow fluorescent cement (BRL) appear to be in alignment with the platelets in the kaolinized mica grains. This pattern probably results from amorphous silica preferentially adhering to the face of kaolinite platelets which Keller (1982) reported. The yellow fluorescence of these cements is probably produced by the aromatic component of humic substances tied to the amorphous silica as an organo-siliceous complex.

Similarly, yellow fluorescent cement (BRL) saturates the deformed detrital kaolinite aggregates in distal Ione sandstones in the same manner as in the Manzanita Oxisol (Photo 12). Langston and Pask (1969) reported that the amorphous silica cement saturating fine-grained kaolinite in Ione sandstones adds considerable stability to the clay aggregates.

Minute opaque particles occur dispersed in the fabric of the clay aggregates and O-F cement is commonly concentrated at their margins (Photo 27 and 29). These opaque particles and concentrations are probably the result of ultrafine microvoids trapped in the kaolinite fabric saturated with amorphous silica cement. The microvoids appear as a diffuse cream or pale yellow color in white reflected light because of light dispersion. The O-F and P-F appearance of these materials are undoubtedly the petrographic manifestation of amorphous silica cement.

Some of the patterns of O-F cement in the kaolinite aggregates show the effects of deformation produced by impinging hard framework grains (Photo 29). The pressure induced by impinging quartz grains similarly caused platy kaolinite particles to realign and drape around the margins of the rigid grains (Criteria 4, above–Dickinson, 1970). The higher birefringence of the clay fabric adjacent to the margins of impinging grains is a consequence of this preferred alignment (pressure realignment) of the planar clay platelets (Photo 30).

Backscattered electron images show that many of the kaolinite aggregates possess an aggregate microfabric similar to the pedogenic kaolinite in the Manzanita Oxisol (compare Photos 9 and 26). This aggregate microfabric combined with organo-siliceous cement saturating the clay fabric probably enhanced the stability of the clay aggregates sufficiently to facilitate transport as bedload sediment in Ione streams.

<u>Mudstones</u>. Fine-grained kaolinite mudstone deposits are sporadically interbedded among Ione sandstones in the Ione area with the thickest deposits occurring in the west side of the Ione basin at Jones Butte, the Bacon pit, and areas to the northwest (Fig. 5). The mudstone deposit that occurs at Jones Butte is historically known as the Edwin clay (Bates, 1945). These mudstone beds overlie the thick lateritic paleosol developed on the basement rocks. The lower mudstone beds were weathered following deposition and appear red from iron oxide staining. The upper white Edwin clay beds at Jones Butte along with those exposed in the nearby Bacon mining pit superficially resemble the fine-grained massive white clay fabric in the upper pallid zone of the Manzanita Oxisol. In fact, *in situ* chemical weathering in a secondary soil profile was suggested by Rodgers (1986) as the origin of the white Ione clay in this region. However, petrographic and SEM analysis shows that there are distinct differences between the clay fabric of these mudstones and the fabric of oxic soil materials in Oxisols that may superficially resemble one another in outcrop.

In thin section, the Bacon pit and Jones Butte mudstones exhibit a homogeneous fabric indicative of disaggregated clay (PPL); however, clay flakes of distinctly higher birefringence are visible (XPL). SEM images show that the clay flakes are microaggregates comprised of discrete kaolinite platelets as small as a fraction of 1 μm in diameter oriented in a face to face arrangement (Photo 18). These small clay aggregates are 5–15 μm or more in length and are oriented both face to face and edge to face with respect to adjacent aggregates. This microaggregate clay fabric is distinctly different from the random arrangement of clay particles characteristic of the bioturbated zones of oxic soil materials (Photos 17 and 18). These clay microaggregates in the mudstones may have been derived from larger sand-sized clay aggregates that were disaggregated during fluvial transport. Another source was probably from discrete clay platelets that flocculated to form microaggregates while in transport as suggested by Alberts *et al.* (1980). The mudstone fabric comprised of these small oriented clay aggregates possesses a higher birefringence compared to the thoroughly homogenized soil fabric of the upper pallid zone (oxic horizon) of the Manzanita Oxisol.

Another distinct difference in the clay fabric of these two environments is that the oxic soil material in the Manzanita Oxisol possesses significant packing void and microped development, whereas, the mudstone fabric lacks these diagnostic features of soil development.

Petrographic examination shows that large areas of the mudstone fabric are also bioturbated. However, the mudstone fabric is denser than the bioturbated fabric of oxic soil material. Bioturbation in fluvial and lacustrine muds by aqueous burrowing organisms apparently results in denser clay fabric compared to the porous clay fabric produced by terrestrial burrowing soil fauna and rooting.

Based on the observation of bedding structures visible in Edwin clay outcrops, Bates (1945) agreed with Allen's (1929) conclusion of a sedimentary origin for these kaolinite mudstone deposits. The presence of sedimentary structures and a fabric comprised of clay microaggregates collectively point to a depositional setting in which fine clay particles settled out of suspension in a standing body of water.

<u>Kaolinite Sedimentology</u>

<u>Sandstones</u>. In facies studies by Rodgers (1986), paleocurrent indicators in Lower Ione sediments in the Ione area show that streams were flowing in an east to west direction. This westward flow direction is reflected in sediment textures of the various Ione sandstones. Petrographic observations of samples from a east to west trending transect from Apricum Hill to Jones Butte show that the modal grain size of quartz sand gradually decreases towards the west

(Fig. 11). This grain size decrease reflects the waning hydrodynamic flow regime of the low gradient braided Ione streams as they flowed further into the Ione basin and gradually lost kinetic energy. The hydrodynamic flow regime similarly controlled the modal grain size of detrital kaolinite clasts transported as bedload sediment (Fig. 11).

In sandstones exposed at Apricum Hill, quartz and kaolinite aggregates are concentrated in the lower medium and lower coarse grain sizes, respectively (Fig. 11). A difference of approximately 1.0 ϕ 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 ϕ separation still exists between the clast size of quartz and kaolinite clasts. 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 clearly shows the difference in clast size produced by the density differences between hydrodynamically equivalent quartz and clay aggregates (Photos 24 and 27).

Figure 11

Grain size relationship of quartz and detrital clay aggregates in Lower Ione sandstones in the Ione area.

Modal Grain Size		vfl		vfu		fl		fu		ml		mu		cl		cu	
ϕ	4.0		3.5		3.0		2.5		2.0		1.5		1.0		0.5		0.0
Location* (Sample#)																	
Apricum Hill (#89-10)										Q				K			
Apricum Hill (#89-09)								Q				K					
Wallens Pit (#91-19)							Q				K						
Old Sand Plant (#91-17)						Q				K							
Owens-Illinois Pit (#91-16)				Q				K									
Jones Butte (#92-12)		Q				K											

Q = quartz, K = sand-sized kaolinite aggregates

* Locations are shown in Figure 5

A similar grain size shift occurs for the kaolinized mica grains in the sandstones. However, the average grain size of kaolinized mica is slightly larger than for kaolinite aggregate clasts. A plausible explanation is that the planar surfaces of the kaolinized mica grains may have performed like minute hydrofoils and contributed some amount of buoyancy to the grains during transport. Therefore, because of additional buoyancy, larger kaolinized mica grains would have been hydraulically equivalent to slightly smaller kaolinite aggregate clasts.

In addition to a reduction of the overall clast size of kaolinized micas, the waning hydrodynamic flow regime may have also been a factor controlling their particle shape. In the medium- to coarse-grained sandstones at Apricum Hill, the kaolinized mica grains commonly occur as "books" with their dimension in the direction of the "c" crystallographic axis approximately equal to, or larger than, the dimension in the direction of the "a-b" axes. Some of the largest kaolinized mica grains are up to 1–2 mm in diameter and a few reach lengths of 2–3 mm in the "c" direction (ie., they appear as sand-sized worm-shaped books). Not only is there a notable reduction in size of the equant kaolinized mica clasts with decreasing sandstone grain size, but also a gradual transition to particles with much shorter dimensions in the "c" direction. For example, in the fine-grained sandstone from the Owens-Illinois sand pit, a greater percentage of kaolinized micas occur as flakes with a much shorter "c" dimension. These platy particles are probably concentrated in the finer grained sands because the hydrofoil effect of their grain shape would have given them greater buoyancy compared to equant grains. Consequently, the platy grains would have been transported farther and concentrated in finer grained sediments. These platy flakes may have originated from the delamination of larger kaolinized mica books. Alternatively, since the Ione streams crossed major belts of metamorphic lithologies in the course of their flow to the west (Allen, 1929), the platy kaolinized mica particles may have originated, in part, from weathered micaceous metamorphic rocks, such as schists and gneisses, in which micas with similar aspect ratios predominate.

Disaggregated detrital mud can be recognized in Ione sandstones by its homogenous "dirty" fabric (PPL), lower birefringence (XPL) produced by the randomly oriented particles (isotropic), and its occurrence in laminae. Disaggregated detrital mud is virtually absent from the coarser grained sandstones at Apricum Hill and the Wallens pit. However, disaggregated mud occurs as discontinuous laminae in the well sorted fine-grained sandstones at the Old Sand Plant and as continuous laminae in the Owens-Illinois pit sandstones. Disaggregated clay was probably washed out of the coarser grained sediments at the time of deposition, but remained as laminae in the finer grained sands because of the lower energy flow regime.

Fine-grained sediments at Jones Butte were deposited at the extreme western margin of the Ione basin and farthest from the sediment source. At this location, streams were probably less energetic than at points in the eastern part of the Ione basin. Here, much of the clay in these fine-grained muddy sandstones is in the form of disaggregated detrital mud. In some sandstones the volume of disaggregated mud is greater than the volume of detrital clay aggregates (Photo 28). In such cases, clay aggregates are easily recognized by their subspherical shape and their coherent "clean" fabric compared to the enveloping mud. The spherical shapes of some clay clasts were preserved because of the large volume of enveloping mud which protected them from significant compression between quartz grains.

<u>Mudstones</u>. The mudstone deposits probably represent overbank accumulations of fine mud adjacent to active fluvial channels. The hydrodynamic flow regime of the adjacent channels probably also controlled the grain size of kaolinite particles occurring in these mudstone deposits. For example, Bates (1945) reported distinct differences in clay particle size in mudstone deposits from opposing sides of the Ione basin. He noted that mudstones at the eastern side of the basin are characterized by both coarser kaolinite and quartz particles compared to the western deposits. He also noted that the eastern clays contain a greater abundance of heavy minerals than their western counterparts. Bates (1945) suggested that this westward textural fining was a consequence of Ione fluvial channels flowing into the Ione basin from the east with the finest kaolinite particles settling in quieter water at the western margin of the Ione basin.

Post-depositional Weathering of Distal Ione Sediments

The most obvious sites to begin a petrographic study of post-depositional weathering are prominent paleosols exposed near the top of the Lower Ione section. Three paleosols examined in this study are located at Jones Butte, Lanes, and Apricum Hill (Fig. 5). So as not to overlook any possibility for an occurrence of authigenic kaolinite, several thick white Ione sandstone deposits unrelated to paleosols were also examined for post-depositional weathering features.

Tertiary Paleosols. Two paleosols with similar characteristics and marked by a distinct red horizon of iron oxide staining occur at Jones Butte and Lanes (Fig. 5). The paleosol at Jones Butte is developed on white kaolinitic sandstones that overlie the Edwin clay. The weathering profile at Lanes is developed in mudstones and overlying conglomeratic sandstones.

The weathering horizon above the iron oxide cemented zone of both paleosols is developed in porous sediments. The major weathering feature characteristic of this upper horizon in both paleosols is the occurrence of pervasive pore-lining illuvial clay coatings. At Jones Butte this weathering horizon is developed in a white, poorly sorted, medium-grained sandstone (#92-14). Petrographic images show that quartz grains are the only remaining framework grain constituent following weathering. All weatherable minerals and clay aggregates were respectively dissolved and disaggregated leaving open dissolution pores. All clay occurring in this weathered sandstone is in the form of illuvial clay coatings which line most of the pores in a similar manner as depicted in Photo 20. No recognizable or distinctive clay particle morphologies remain.

The illuvial clay mineral assemblage of the Jones Butte sandstone (XRD 20) is similar to that occurring in underlying sandstones in which the effects of weathering are minimal (#89-29, XRD 17). In the lower sandstones, kaolinite is in the form of detrital mud, clay aggregates and kaolinized mica with no illuvial clay. Therefore, the illuvial clay in the weathered sandstone (#92-14) probably developed from detrital crystalline forms that were later disaggregated by soil processes. The XRD analysis also shows that the clay assemblage of sample #92-14 has a trace amount of smectite similar to the nearby Bacon pit mudstone (XRD 18). The smectite may have formed authigenically; however, as illuvial clay is the only clay morphology present, the smectite was probably a component of the original detrital clay assemblage and was merely translocated through the weathering profile. Smectite occurs as smaller particle sizes and would have been more susceptible to translocation. Thus, the smectite could have been derived from smectitic sediments higher in the section. For example, the Valley Springs Fm. (rhyolitic ash) is merely a few meters higher in the section.

At Lanes, the porous sediments above the red zone of the paleosol are comprised of a sequence of sandstones interbedded with conglomeratic sandstones. These sandy units are horizontally bedded and the original depositional fabric is intact. The sediments are poorly sorted and have a large volume of primary porosity . Most of the primary pores of these sandstones are partially or completely lined with illuvial clay coatings indicative of a weathering horizon. However, detrital clay aggregates in the sandstone fabric appear intact. Therefore, the illuvial clay was probably translocated from a zone of eluviation in an overlying horizon of the soil profile.

The weatherable mineral components of metamorphic rock fragments were dissolved either prior to transport or *in situ* leaving skeletal grains solely composed of quartz. No authigenic crystalline clay is apparent in primary or secondary pores.

Another weathering feature in this conglomeratic horizon is the occurrence of O-F cement coatings in many of the clay aggregates and in disaggregated detrital mud. The coatings appear to be in similar stages of development in all occurrences which indicates *in situ* development. Petrographic observation shows that iron oxide cement, probably goethite (bright yellow), is restricted to pore-lining illuvial clay and O-F cement coatings. This iron oxide cement imparts a slight yellow coloration to the sandstones in outcrop.

In both paleosols the prominent red zone of iron oxide cement occurs in relatively clayey beds of low porosity and permeability below the coarser, porous sands previously described. At Jones Butte, a 0.5 meter thick red horizon occurs in a very fine-grained sandstone (#92-12). This sandstone has virtually no intergranular porosity because of the large volume of clay occurring in it. Clay in the form of detrital mud and clay aggregates constitutes approximately 80% of the volume of this sandstone. Post-depositional compaction of the clay obliterated what little primary porosity might have initially existed.

Petrographic observation shows that the sedimentary fabric of the sandstone is intact and iron oxide cementation appears to be merely superimposed on the sedimentary fabric. Both hematite and goethite cements occur in the fabric based on the bright red and yellow colors, respectively (WRL). In spite of the iron oxide cement staining the sandstone fabric, many amphibole grains in the sandstone show no signs of oxidation or dissolution.

At Lanes the prominent red zone of iron oxide cement is developed in a silty mudstone bed below the erosional contact with the overlying conglomeratic sandstones. Immediately below the contact, an indurated zone of iron oxide cement 6–10 cm thick that could be described as a ferricrete is developed in the mudstone. Below the ferricrete the mudstone exhibits iron oxide masses and redoximorphic features (mottling) to a depth of 1–2 meters. The intensity of the red color and degree of development of iron oxide redoximorphic features gives the impression that intense weathering occurred in this horizon. However, petrographic observation shows that the fabric of the mudstone both in the zone of mottling and in the white unaltered material below is similar to the unaltered clay fabric of the Edwin and Bacon pit mudstones. It appears that iron oxide cement in the mottled zone is merely superimposed over the mudstone fabric. Silt size amphibole grains occur in the mottled zone and many remain in pristine condition.

A significant effect of the weathering profile on this mudstone substrate was the development of fractures and minor accommodated packing voids which occur throughout the clay fabric. The packing voids were probably a consequence of shrinking and swelling of the clay fabric in response to paleo-groundwater fluctuations. O-F cement coatings occur in the clay fabric symmetrically and equidistant from the packing voids and are probably of organo-siliceous composition. The packing voids were the only apparent avenues for groundwater solutions to move through this otherwise impermeable horizon of the weathering profile. The occurrence of the O-F cement associated with the fractures is evidence that the fractures were not produced by desiccation during sample handling.

In the paleosol at Jones Butte, O-F cement coatings similarly occur in the fabric of the white muddy sandstone (#89-29) which lies 0.5 m below the red iron oxide zone. The O-F coatings form elongate enclosures with lengths of 1–3 mm; however, in this sandstone the coatings are not associated with packing voids (Photo 28). The coatings cross the matrix of the sandstone fabric indicating *in situ* development. Amphibole grains occurring in the sandstone show no signs of dissolution or oxidation. All kaolinite is in the form of detrital clay aggregates and disaggregated detrital mud.

The weathering profiles at Lanes and Jones Butte are similar in many ways. Both are characterized by an upper weathering horizon developed on porous and permeable sandy units. The major weathering feature of this horizon is the occurrence of pervasive illuvial clay. The underlying horizon is a zone of iron oxide precipitation developed on clayey beds of poor permeability. The concentration of the iron oxide cement in the clayey beds underlying highly porous beds suggests that iron oxide cement precipitated when iron-rich leachate solutions moving down through the weathering profile encountered a zone of poor permeability. O-F cement coatings occur in sediments of both weathering profiles below the zone of iron oxide cement, which indicates that the leachate solutions moving through the weathering profiles were also siliceous-rich. The siliceous- and iron-rich solutions were probably derived from the dissolution of weatherable minerals in the upper horizons of the soil profile closer to the paleosurface.

Another prominent paleosol with features similar to those at Jones Butte and Lanes is exhumed at Apricum Hill (Fig. 5). Singer and Nkedi-Kizza (1980) interpreted this paleosol as a profile of deep weathering which they classified as an Oxisol. They concluded that intense weathering under tropical conditions resulted in the highly kaolinitic composition of the weathered residuum. The Apricum Hill paleosol is probably contemporaneous with the paleosol at Lanes. A similar prominent paleosol occurring at the contact of conglomeratic sandstone units and underlying finer grained sediments can be traced south from Lanes towards the Apricum Hill exposure. The facies change represented by the overlying conglomeratic sediments plus the widespread occurrence of the weathering horizon at this textural boundary suggests that a significant hiatus of Ione deposition occurred.

Pleistocene erosion probably removed the overlying conglomeratic sandstone unit and upper horizon of the paleosol at the Apricum Hill site. Singer and Nkedi-Kizza (1980) also concluded that the upper A1 horizon of the Apricum Hill soil profile was apparently removed by Pleistocene erosion. The prior existence of this overlying coarse-grained horizon is indicated by a residual lag of well rounded quartz cobbles that sits on the indurated surface of the exhumed paleosol.

The upper-most horizon of the Apricum Hill paleosol (still remaining) is characterized by a 0.5 meter thick indurated ferricrete developed at the top of the well sorted Lower Ione sandstone section. Below the ferricrete is a 2–3 meter thick zone of iron oxide precipitation forming redoximorphic masses and segregations (mottling). This iron oxide zone was classified as an oxic horizon by Singer and Nkedi-Kizza (1980). They reported that this paleosol meets the criteria of an Oxisol because it possesses the morphologic, chemical, and mineralogical requirements of an oxic horizon set by the USDA (Soil Survey Staff, 1975). Their data show that because of the high kaolinite content in the paleosol, the cation exchange capacity of the clay assemblage is within the limits set for Oxisols (Soil Survey Staff, 1975).

It now appears that Singer and Nkedi-Kizza (1980) overestimated the degree of weathering associated with this paleosol. For example, the high kaolinite content that they attributed to *in situ* weathering is, in fact, merely the clay composition of the pre-existing Lower Ione sediments. XRD analysis shows that the clay composition of the sandstone substrate in their "oxic horizon" (#89 12) is virtually the same as for sandstones 7–8 meters below the paleosol (#89-09) as well as all the other Lower Ione sandstones in the Ione area (XRD 17). In addition, petrographic examination shows that kaolinite in the sandstone substrate in the mottled zone occurs in the form of detrital kaolinite aggregates and kaolinized mica.

Singer and Nkedi-Kizza (1980) also attributed the paucity of weatherable minerals in this weathered sediment to post-depositional weathering in a highly leached soil rather than to the unique character of the Ione sediments at the time of deposition. Petrographic studies here show that sandstone in the "oxic horizon" (#89-13) actually contains as many weatherable minerals as do unaltered sandstones 7–8 meters below (#89-09). Granted, amphibole grains occur in trace quantities in these sediments, but they are common in laminae concentrated with heavy minerals in Lower Ione sandstones. In the zone of the ferricrete at the top of the weathering profile (#89-14), petrographic examination indicates that the effects of oxidation on iron bearing minerals are severe. However, one meter below the ferricrete in the middle of the mottled zone (#89-13), amphibole grains show only minor effects of dissolution or oxidation. Many amphiboles exhibit no signs of oxidation at all (Photo 32).

The notion that iron bearing minerals could escape oxidation in the zone of intense iron oxide coloration seems implausible; however, strong iron oxide coloration such as that exhibited in the mottled zone of this paleosol can be produced by an iron oxide content of only a few percent (Schwertmann and Taylor, 1989). Petrographic observation shows that the red coloration in the mottled zone is primarily produced by iron oxide precipitation in the kaolinite pseudomatrix of the sandstones and not from severe oxidation of iron bearing minerals.

XRD analysis shows that goethite is the predominant iron oxide phase occurring in the mottled zone of the paleosol (XRD 17). Petrographic images show that goethite cement is associated with the kaolinite pseudomatrix of the sandstones (Photo 32). Although hematite is not detectable in XRD analysis, it occurs associated with laminae of heavy minerals and O-F cement coatings concentrated along the margins of clay aggregates forming the pseudomatrix. Even in trace amounts, hematite has a stronger pigmenting ability than goethite (Schwertmann and Taylor, 1989) and its red color overwhelms the yellow color of goethite in the Apricum Hill paleosol.

The distribution of iron oxide cements in the sandstone substrate associated with the kaolinite pseudomatrix and adhered O-F cement suggests that much of the iron oxide coloration in the mottled zone was produced by the oxidation of iron chelated with organo-siliceous cements that permeate the clay pseudomatrix. The distribution of goethite and hematite in the sandstone substrate corresponds to the relationships reported by Schwertmann and Taylor (1989) for the precipitation of organic iron—the slow release of chelated iron from the oxidation of organic matter favors goethite precipitation while hematite forms when there is an increase in the rate of iron release or greater iron availability. Iron bearing minerals and higher concentrations of organo-siliceous cement in O-F coatings probably supplied additional iron which led to the associated hematite precipitation.

White Ione sandstone (#89-10) lying 0.5 meters below the iron oxide mottled zone of the Apricum Hill paleosol does not appear to have been significantly affected by the overlying weathering profile. O-F and P-F cement coatings occur in individual clay aggregates; however, these cements do not appear to be in similar stages of development. No O-F cement coatings cross the sandstone fabric in the same manner as in equivalent horizons of the Jones Butte and Lanes paleosols. Therefore, *in situ* development of O-F coatings is not indicated. Minor accommodated fractures occur throughout the pseudomatrix composed of compacted clay aggregates. As no O-F cement coatings occur in association with these fractures, their development in response to the overlying weathering profile is not conclusive. The fractures could have developed *in situ* in response to soil processes. Alternatively, they may have developed from desiccation during sample handling or thin section preparation.

The ferricrete at the top of the paleosol at Apricum Hill is similar to the one occurring in the same position in the paleosol at Lanes. It probably originated in the same way—mineral dissolution occurring in the overlying soil horizon in the conglomeratic sandstones (later eroded) probably contributed iron-rich solutions to the groundwater. Iron oxide precipitation was probably concentrated at the top of the underlying well sorted kaolinitic sandstones as the iron-rich groundwater solutions encountered the layer of relatively impermeable clayey sandstones. Apart from the oxidation of weatherable minerals in this upper ferricrete horizon, the weathering profile at Apricum Hill does not appear to have had a significant effect in altering the fabric or mineralogy of the underlying sandstone substrate. The effects of weathering associated with this paleosol diminish rapidly with depth and Ione sandstones merely 0.5 meters below the zone of iron oxide mottling exhibit little or no effects of weathering.

<u>White Ione Sandstones</u>. Kaolinitic Ione sandstones are exposed in several mining pits in the Ione area. Representative samples of thick white deposits of Lower Ione sandstones were taken from exposures at Apricum Hill, the Wallens pit, Old Sand Plant, and the Owens-Illinois pit. These sandstones contain 50% or more of kaolinite by volume and have a low content of weatherable minerals (Appendix D).

The large volume of kaolinite combined the with the near absence of weatherable minerals in Ione sediments lends credence to the notion that chemical weathering under a tropical climatic regime severely altered the original sediment composition leaving a paucity of weatherable minerals. However, weatherable minerals are not absent in Lower Ione sediments. Feldspar and amphibole grains occur in trace amounts in every Lower Ione sandstone sample examined from the Ione area. Most of the distal Ione sandstones are well sorted and amphibole grains are typically concentrated with heavy minerals along laminae. All of the white kaolinitic Ione sandstones contain at least 6–10 amphibole grains per thin section. EDX analysis of a typical amphibole grain from the sandstone at Apricum Hill (#89-09) shows the cation composition of hornblende containing Na, Mg, Ca, and Fe in addition to Al and Si (EDX 7). Amphibole grains in white Ione sandstones appear to be in pristine condition and show no signs of dissolution or oxidation. Although K-feldspar is more resistant to weathering than amphibole (Goldish, 1938; Chamley, 1989), it eventually dissolves with chemical weathering under prolonged tropical conditions. Disregarding the feldspar fragments that occur embedded in detrital pedogenic clay clasts, the few discrete feldspar grains occurring in the sediments similarly show little or no effects of weathering.

Characteristics of the Ione sandstone fabric provides additional negative evidence of post-depositional weathering. Petrographic observation shows that features of the depositional fabric such as laminae are undisturbed. In outcrop, sedimentary structures such as cross bedding and sporadic trace fossils are distinct. Packing voids diagnostic of soil development do not occur in the clay fabric of the white Ione sandstones examined.

The sample from the Owens-Illinois pit (#91-16) is the only example of the white Ione sandstones that possesses any features indicative of *in situ* pedogenic processes. Minor O-F cement coatings occur dispersed in the fabric of this sandstone similar to the coatings occurring in the sandstone below the paleosol at Jones Butte (#89-29). Similarly, the coatings in this sandstone are also unassociated with fractures in the fabric. They form sinuous elongate enclosures 1–2 mm long which cross the sandstone fabric, indicating *in situ* development.

Other unique features occurring in sandstone #91-16 are iron oxide micronodules of up to 1.0 mm in diameter that are dispersed in the fine-grained sandstone fabric. They are red in white reflected light and have the appearance of sand-sized rust spots in hand specimen. Petrographic examination shows that the micronodules possess a massive internal fabric with some exhibiting slightly darker colored concentric bands which suggests that they grew in concentric layers ("microconcretions"). The micronodules do not appear to have nucleated around oxidized iron-bearing mineral grains as no discernible grains appear within them. They did not envelope any of the fine-grained quartz grains. The perimeter of some is marked by the outline of minute euhedral iron oxide crystals producing a serrate grain margin. At first glance, this crystalline grain margin and their large size compared to the well sorted fine-grained quartz fabric suggests an authigenic *in situ* origin. However, no iron oxide cement occurs in association with the O-F cement in the adjacent clay aggregates and amphibole grains that occur in the sediment similarly show no signs of oxidation.

A solution to the origin of these alien grains comes from an examination of the mudstones in the Gladding McBean mining pits at Lincoln. Similar red iron oxide micronodules are abundant in one bed of the "Lincoln 7" mudstone. Petrographic observation shows that the micronodules developed *in situ* in this mudstone. They appear in all stages of development from silt-sized nuclei up to 1.0 mm and greater. All possess serrate grain margins comprised of minute hematite crystals. Their internal structure is similar to those in the Ione sandstone—massive with some exhibiting darker colored semi-concentric bands. Most have enveloped only fine-grained clay resulting in the massive internal structure. However, a few micronodules enveloped a grain or two of silt-sized quartz that occur in the mudstone fabric.

All evidence points to a detrital origin for the hematite micronodules in the Ione sandstone (#91-16). They probably formed in an exposed local mudstone bed and were reincorporated into the sandy sediments by fluvial reworking. Although many of the micronodules have a serrate grain margin, many show signs of abrasion with rounded boundaries. Occasional quartz grains occur in this sandstone with the same modal grain size as the micronodules resulting in a bimodal sandstone texture. Adjacent clay clasts are deformed at the margins of these micronodules suggesting that the micronodules compressed the clay matrix during post-depositional compaction.

Although sandstone #91-16 exhibits no other weathering features, the occurrence O-F cement suggests that an overlying weathering horizon may have originally existed some distance above this sandstone which supplied siliceous-rich leachate solutions to the groundwater. The style of bedding in the walls of the mining pit is that of amalgamated braided fluvial deposits. Although no paleosol is visible in the mining pit walls, fluvial reworking may have stripped away an earlier weathering profile.

<u>Holocene Weathering</u>. Additional evidence suggests that the white kaolinitic Ione sandstones are actually very sensitive to oxidation and prominently exhibit the effects of incipient weathering. White Lower Ione sandstones are exposed in the roadcut on Hwy 124 south of Ione across from the NARCO plant (Fig. 5). The sandstones exposed at the face of the outcrop exhibit significant iron oxide discoloration with various yellowish brown colors.

Petrographic observation of a weathered sandstone sample from the face of the roadcut (#92-02) shows that the iron oxide coloration in outcrop is produced by goethite cement disseminated in the clay pseudomatrix of the sandstone. There appears to be two associations of goethite cement in the weathered sandstones. In one occurrence, goethite is associated with O-F cement permeating kaolinite aggregates (Photo 31). Petrographic images show that the arrangement of goethite cement occurring in the clay aggregates is similar to the spatial arrangement of O-F cement in clay aggregates in unoxidized sandstones (Photo 29). Greater concentrations of goethite cement occur along O-F coatings at the margins of some clay aggregates (Photo 31). The source of iron for goethite associated with the kaolinite aggregates was probably iron chelated with organo-siliceous cement. Goethite probably formed from the slow release of chelated iron when organic matter in the organo-siliceous cements was oxidized during prolonged exposure in the face of the roadcut.

Some sandstone beds and laminae with a greater abundance of heavy minerals are severely cemented by iron oxide cement. These particular zones stand out in bold relief in the face of the outcrop because of differential weathering. Petrographic images show that concentrations of goethite cement occur adjacent to oxidized iron bearing minerals. Both the macro- and microscopic associations suggest that the oxidation of iron bearing minerals such amphibole and magnetite was an additional source of goethite cement in the sandstones exposed at the face of the outcrop.

Ione sandstones exposed at the face of the roadcut exhibit prominent discoloration and associated weathering features while only a few centimeters beneath the weathered face of the outcrop, Ione sediments remain white and amphibole grains show no signs of oxidation. This example shows that this superficial weathering was produced solely as a result of only a few decades of subaerial exposure under the modern temperate climate. It also illustrates the sensitivity of Ione sediments to the effects of surface weathering even under temperate conditions.

DISCUSSION

Origin of Kaolinite

Petrographic evidence shows that kaolinite occurring in both proximal and distal Lower Ione fluvial sediments is primarily in the form of detrital sand-sized clay aggregates, kaolinized mica, and disaggregated mud. Kaolinite in Ione sediments meets the multiple criteria defined by Dickinson (1970) and Wilson and Pittman (1977) to be classified as detrital clay in the form of argillaceous lithic fragments. Detrital clay aggregates in Ione sediments possess characteristic pedogenic micromorphologies which differ from those of pore-filling authigenic kaolinite, indicating that Ione kaolinite was derived from the erosion of local Oxisols and related kaolinitic soils. This conclusion is supported by the occurrence of pedogenic organo-siliceous cements that saturate kaolinite aggregates in Ione sediments.

The fluvial flow regime in Ione channels appears to have been the most important factor in determining the abundance and morphology of kaolinite clasts in Ione sediments. Kaolinite aggregate clast size was controlled by the fluvial flow regime analogous to other detrital clasts such as quartz and heavy minerals. The consistent difference in the modal grain size of clay aggregates verses quartz in well sorted Ione sediments indicates that these two major constituents were hydrodynamically equivalent and that kaolinite aggregate clasts were transported as bedload sediment in Ione fluvial systems.

Vermicular kaolinite morphologies are common in the matrix (pseudomatrix) of Ione sandstones. Considering the distances involved from source areas to the Ione basin, it is not likely that such delicate crystalline forms could have been transported those distances in the energetic fluvial environment and remained intact as discrete particles. However, such morphologies imbedded within stabilized clay clasts apparently did withstand bedload transport and a substantial volume of clay in this form reached the basin.

Detrital clay clasts were undoubtedly disaggregated in all reaches of the fluvial system with the disaggregated clay becoming part of the suspended load. The disaggregation of clay clasts in the distal reaches of the fluvial system could conceivably have allowed discrete vermicular kaolinite forms to be carried from the main fluvial channels into adjacent fine-grained muddy interdistributary or overbank deposits on the floodplain. In a similar argument to the coarser grained sediments, two features would support a detrital scenario for an occurrence of such vermicular forms in floodplain mudstones: 1) sericite, an important genetic precursor, should be associated with the vermicular kaolinite, and 2) silt-sized weatherable mineral grains should occur in the sediment.

Detrital clay aggregate stabilization was probably facilitated by the combination of the aggregate micromorphology of pedogenic kaolinite and additional pedogenic cements of siliceous composition inherited from source soils. Flach *et al.* (1969) and Singh and Gilkes (1993) noted that even small amounts of silica are effective cements stabilizing clay aggregates in soils and inhibit dispersion. Langston and Pask (1969) noted the similar effect of amorphous silica cement in inhibiting the mechanical disaggregation of clay aggregates in Ione sandstones. These pedogenic cements are manifested as O-F and P-F morphologies in detrital clay aggregates in Ione sediments and were ultimately a crucial factor in the determination of the Ione sediment lithology. The understanding of the sedimentology of a tropical river system such as the Ione would be incomplete without addressing the role of pedogenic cements in facilitating the fluvial transport of such a large volume of otherwise delicate argillaceous sediment.

The Recognition of Pedogenic Cements

Brewer and Sleeman (1969) noted that in spite of the release of large amounts of silica by chemical weathering in mature soils, the occurrence of secondary pedogenic silica is infrequently reported. They attributed this to the optical properties of amorphous silica which make thin films of this material difficult to detect in the clay fabric of soils. Singh and Gilkes (1993) noted that pedogenic amorphous silica occurring as a diffuse cement in the clay matrix of soils possesses a nondescript morphology and can not be isolated and analyzed by standard techniques. For example, they also reported that optical microscopy is ineffective in detecting isotropic amorphous silica occurring at a submicron scale homogeneously distributed in the clay matrix of soils. In addition, they showed that X-ray diffraction techniques may be ineffective at detecting minor amounts of amorphous silica. While high concentrations of amorphous silica occurring in a lateritic hardpan from their study showed a broad diffraction peak at 0.41 nm reported to be characteristic of opal-A (Jones and Segnit, 1971), Singh and Gilkes (1993) found that up to 20% amorphous silica can occur in soils without an apparent X-ray diffraction signature. These factors help to explain why pedogenic siliceous cements stabilizing detrital clay aggregates in clastic sediments have largely gone unrecognized.

Flach *et al.* (1969) reported that <10% amorphous silica can cement the clay fabric in soils. Singh and Gilkes (1993) reported that only 5% or less effectively cements the kaolinite fabric in the lateritic soil in their study. In this study, the results of microprobe analysis show that the presence of small amounts of amorphous silica in the kaolinite fabric may be manifested in EDX analysis as only a slight Si peak height enhancement over the 1:1 silicon/aluminum ratio of the background kaolinite. This 1:1 ratio of Si/Al in kaolinite makes a Si peak height enhancement attributable to excess silica a reasonable conclusion. However, the detection of small amounts of amorphous silica permeating pedogenic clay with other clay mineralogies, and with variable Si/Al ratios, makes the use of EDX techniques inconclusive if not useless. Although Singh and Gilkes (1993) showed that amorphous silica can be detected in microprobe backscattered electron images through the manipulation of digital data, such advanced techniques are beyond the resources of many workers.

Fortunately, amorphous pedogenic cements may be recognized by zones of clay fabric with pale or opaque morphologies (PPL). These zones exhibit a characteristic pale yellow or cream color with white reflected light. In addition, the complexing of organic matter with siliceous cements conveniently causes these colloidal materials to fluoresce (BRL). The fluorescence is produced by trace amounts of the aromatic hydrocarbon component of humic acids complexed with the silica cement. In blue reflected light, yellow fluorescent cement permeates the clay fabric both in source soils and in detrital kaolinite aggregates in Ione sandstones. Lacking the availability of advanced analytical equipment (ie. microprobe), probably the most effective and practical method of detecting the presence of these organo-siliceous cements in pedogenic clay materials is the combination of these various optical petrographic techniques (ie., PPL, WRL, and BRL).

Petrographic evidence indicates that the oxidation of iron chelated with pedogenic organo-siliceous cements occurs in the earliest stages of subaerial weathering of Ione sediments. Thus, the strong coloration of Ione sediments with incipient weathering prior to the occurrence of significant weathering effects on iron-bearing minerals such as amphibole is a further indication of the presence of pedogenic cements in Ione sediments.

Chemical weathering leading to the dissolution of silicate minerals is a process that occurs in soils from a wide range of climatic regimes. Consequently, amorphous silica cement undoubtedly occurs in the clay fabric of many soil types with differing clay mineral assemblages. Thus, if amorphous silica is not uncommon in soils and in light of the difficulty of recognizing small amounts of amorphous silica in pedogenic clay materials, another question becomes apparent—is amorphous silica the universal “super glue” that facilitates the transport of detrital argillaceous lithic fragments (pedogenic clay clasts) as bedload sediment in many modern fluvial systems? Further, does such nondescript cement account for the occurrence of detrital clay clasts abundant in many fluvial and marine sandstones?

Indeed, the occurrence of organo-siliceous cements stabilizing detrital clay is not merely restricted to the Ione depositional system. For example, O-F cement morphologies are apparent in detrital pedogenic clay clasts abundant in Sespe Formation fluvial sandstones (Eocene) from coastal California. Thin section examination shows that the iron oxide staining associated with the prominent “red beds” of the Sespe Fm. is largely caused by disseminated goethite and hematite cements that are restricted to the clay matrix (pseudomatrix) of the sandstones.

In another example, petrographic and microprobe analyses of kaolinitic Huber Formation sandstones (Early Tertiary) from the Harrison Mine in the Middle Georgia Kaolin District provided by Robert Pruett (ECCI) show that kaolinite is largely in the form of sand-sized detrital clay aggregates possessing O-F and P-F cement morphologies indicative of pedogenic organo-siliceous cements. In blue reflected light, yellow fluorescent cements saturate the clay aggregates and individual kaolinite platelets in the Georgia samples similarly to clay aggregates in Ione sediments and in the Manzanita Oxisol such as that shown in Photo 12.

The Recognition of Pedogenic Kaolinite In Ione Sediments

For various reasons the detrital character of Ione kaolinite has escaped recognition in past studies of Ione sediments (MacGinitie, 1941; Gillam, 1974; Rodgers, 1986). In the case of the work on the proximal Ione sandstones near Nevada City by MacGinitie (1941), petrographic studies were conducted on disaggregated mineral separates in which the clay was completely removed from the focus of the study. Thus, the occurrence of clay in the sandstone fabric was virtually ignored.

Ironically, Gillam (1974) also recognized the clay-filled “gaps” (“framework holes”) in the sedimentary fabric of Ione sandstones from study sites a few kilometers south of Ione. Fragmentary remnants of feldspar occurring in the fabric of some of the clay-filled gaps, suggesting that weatherable minerals had altered to clay, led her to conclude that the kaolinite-filled gaps were the result of *in situ* chemical weathering of feldspar. If this scenario had been correct, based on her photomicrographs and illustrations, the original diameter of some of the altered precursor feldspar grains would have been 2–3 times the diameter of quartz. However, Gillam’s (1974) photomicrographs and textural descriptions show that the Ione sandstone samples in her study were well to very well sorted implying that feldspar grains should have been hydrodynamically equivalent or roughly the same modal grain size as quartz. In addition, she concluded that other clay-filled gaps were probably devitrified volcanic glass material based on the “isotropic” (low birefringence) appearance of some of the fine-grained kaolinite material. However, her photomicrographs and excellent illustrations show that kaolinite forming the sandstone matrix including the clay-filled gaps in the study samples are actually deformed detrital pedogenic clay clasts that formed pseudomatrix. The clay material depicted in her photomicrographs appears to meet the published criteria for classification as detrital clay (argillaceous lithic clasts) of Dickinson (1970) and Wilson and Pittman (1977) as well as some of the specific criteria for detrital pedogenic kaolinite listed earlier.

Rodgers (1986) used similar arguments to conclude that kaolinite in Ione sandstones from the Ione area formed as a result of *in situ* chemical weathering of feldspathic sediments. He further supported his argument by noting the occurrence of delicate vermicular kaolinite morphologies in his study samples and cited the criterion of Wilson and Pittman (1977) indicating a probable authigenic origin for such clay morphologies. However, results of this study show that delicate vermicular morphologies are characteristic of both pedogenic and authigenic occurrences and an examination of the kaolinite microfabric is necessary to distinguish the two.

It is apparent from evaluating these past studies of Ione sediments that there are a number of characteristics of kaolinite that makes petrographic-based genetic interpretations of its occurrence in clastic sediments difficult compared to other clay minerals. This further illustrates the necessity of a comprehensive approach using multiple criteria to understand the occurrence of an inherently problematic mineral in clastic sediments.

The Effects of Post-depositional Weathering

The physical appearance of the paleosols at Lanes and Jones Butte with their prominent red iron oxide horizons gives the impression that significant weathering and alteration of Ione sediments occurred. However, petrographic examination shows that the sedimentary fabric of Ione sediments in the red iron oxide cemented zones remains intact and significant bioturbation of the fabric is not apparent. Mechanical soil processes did not lead to the homogenization of the soil fabric as in the oxic horizon of the Manzanita Oxisol. The effects of weathering on Ione sediments within these paleosols decrease rapidly with depth such that weatherable minerals are unaffected immediately below the zone of iron oxide precipitation.

Petrographic evidence shows that the red iron oxide coloration giving the appearance of significant weathering is not the result of the oxidation of iron-bearing minerals within the affected sediments, but is probably produced by a combination of two other sources. One source of iron was apparently from the oxidation of iron-rich leachate solutions moving through the weathering profile. The other was probably from the oxidation of iron chelated in organo-siliceous cements that permeate the pedogenic clay sediments.

A crucial indication that these paleosols were not sites of long term chemical weathering is the apparent absence of important pedogenic features diagnostic of mature soil development. In mature soils such as Oxisols, hydrolysis is promoted by the passage of large volumes of groundwater through the soil profile. The avenues for fluid transport through relatively impermeable clayey materials are provided by a network of packing voids and vughs that forms in the course of soil development. In addition, shrinking and swelling of the soil fabric lead to the development of peds or soil aggregates delineated by the packing void network. These pedogenic features are either absent or only poorly developed in the weathering profiles superimposed on Ione sediments.

Petrographic examination shows that authigenic pore-filling kaolinite morphologies do not occur in these profiles as a result of feldspar weathering. The only neoformed clay morphology that resulted from surface weathering in Ione sediments is pore-lining illuvial clay (cutans, argillans) formed by the translocation of pre-existing clay particles. The abundance of illuvial clay alone indicates that these weathering profiles were created by a weathering regime of less severity or duration than what is required for the development of deep weathering profiles such as Oxisols. Oxisols commonly lack all but a trace of illuvial clay because of intense mechanical soil processes.

The weathering features exhibited in the paleosol at Apricum Hill are similar to equivalent horizons in the paleosols at Lanes and Jones Butte. This suggests that the degree of weathering that occurred in the Apricum Hill profile was probably of similar magnitude. The missing upper horizon of the Apricum Hill soil profile, which is preserved at Jones Butte and Lanes, would have permitted a better understanding of the degree of soil development. However, other features of this weathering profile give a good indication of the true degree of weathering involved.

Although Singer and Nkedi-Kizza (1980) showed that the Apricum Hill paleosol possesses the mineralogical and chemical criteria to be classified as an Oxisol, petrographic evidence indicates that the paleosol completely lacks important diagnostic micromorphological features of mature weathering profiles such as packing voids and ped development. In addition, the abundance of only slightly weathered or unweathered amphibole grains in the sediment substrate contradicts the notion of deep chemical weathering associated with this paleosol. This evidence shows that the kaolinitic composition of the sediment substrate of this paleosol was probably not the product of *in situ* chemical weathering, but was actually the unique composition of the Ione sediments at the time of deposition. Thus, Singer and Nkedi-Kizza's (1980) soil analysis actually characterizes the highly weathered source materials from which Ione sediments were derived...Oxisols! Figure 12 illustrates the relationships of soil development and Lower Ione sediments.

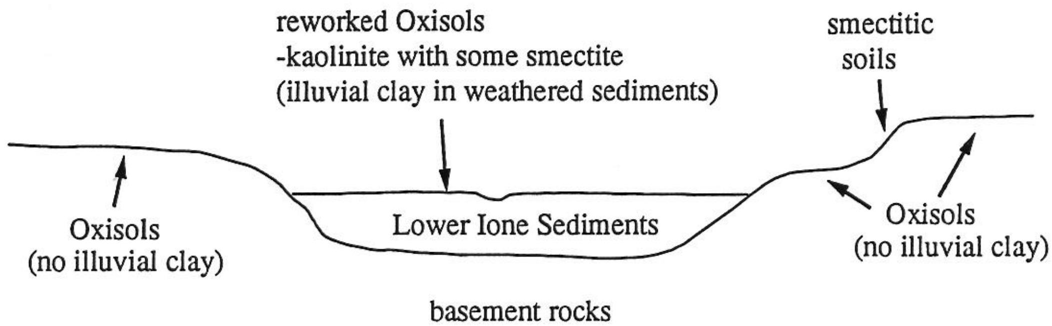


Figure 12
The relationship of soil development with Lower Ione sediments.

The striking effects of weathering on white Ione sandstones in the roadcut on Hwy 124 occurred after only a few decades of subaerial exposure under the modern temperate climate. If the Ione sandstones had been exposed to the tropical early Eocene climatic regime for a sufficient length of time, the sediments would exhibit the effects of severe chemical weathering. However, the bulk of the Ione sediments remain white with no apparent signs of oxidation or dissolution of the weatherable mineral component. Both microscopic and macroscopic sedimentary structures remain intact and important pedogenic features indicative of deep chemical weathering such as packing voids and ped development are absent. The implications of the roadcut analogy are that the white Ione floodplain sediments in distal areas were apparently exposed at the surface for a relatively short period of time ($<10^2$ years) before being buried by subsequent fluvial deposition and were thereby isolated from significant weathering effects of the early Eocene tropical climate. A high ground water table on the floodplain would have preserved the sediments in a reduced state. However, hiatuses in Ione deposition resulting from channel migration left Ione sediments exposed for a sufficient period of time for the development of the weathering profiles that occur sporadically in the distal Lower Ione section. The illuvial clay morphologies (cutans) associated with these weathering profiles indicates soil development leading to the formation of an argillic horizon. Argillic horizons form with soil stability in the range of 10^2–10^5 years (Birkeland, 1984). However, the presence of unweathered amphibole grains only a meter or two below the red zones of these paleosols implies a development time in the lower end of this range ($<10^3$–10^4 yrs).

Important Controls of Lower Ione Sediment Composition

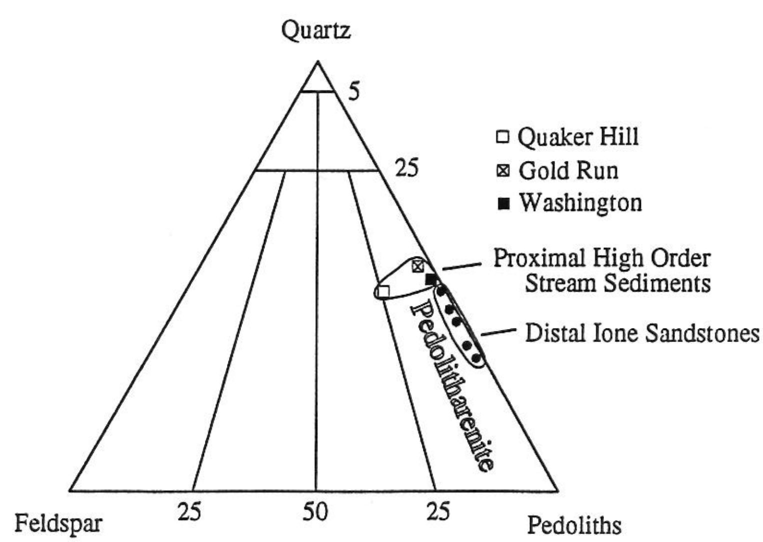
The results of this petrographic investigation show that distal Lower Ione sediments in the Ione area were deposited with the unique kaolinitic composition that they currently possess and were not originally of arkosic composition and altered *in situ* by chemical weathering. Although post-depositional weathering of Ione sediments may not have led to the creation of additional authigenic kaolinite, nevertheless, the weathering of Ione sediment on the floodplain in proximal areas was probably an important process in the ultimate determination of the unique mineral assemblage of distal Lower Ione sediments.

Feldspar and other weatherable minerals occur in only trace amounts in the distal Lower Ione sandstones at Ione as well as in some proximal Lower Ione sandstones near Nevada City (Fig. 13; Appendix D). However, feldspar occurs in greater abundance in other proximal Lower Ione fluvial deposits (eg., Quaker Hill). This disparity in the composition of proximal vs distal sediments was probably the result of a sediment composition maturation process unique to tropical river systems. In modern tropical fluvial systems, the post-depositional weathering of fluvial sediments in long term alluvial storage on the floodplain is an important process controlling the ultimate composition of sediments in the distal reaches of the rivers (Franzinelli and Potter, 1983; Johnsson *et al.*, 1988; Johnsson *et al.*, 1991). Petrographic evidence suggests that this process also operated in the tropical Ione depositional system and was probably an important process contributing to the depletion of weatherable minerals in Lower Ione fluvial sediments.

Although clay assemblages of proximal Lower Ione fluvial deposits near Nevada City are dominated by kaolinite, minor amounts of other clay minerals such as smectite occur (Table 2). The near-monomineralic kaolinite clay assemblage that characterizes most of the distal Lower Ione sediments appears to have been the result of another kind of sediment maturing process or processes.

Figure 13

Lower Ione sandstone compositions in the Folk (1974) classification scheme.



One mechanism to account for this compositional purity in distal sediments may be related to the difference in the dispersibility between smectite and kaolinite. The smectite in the clay assemblages of proximal Lower Ione sediments discussed earlier is a component of pedogenic clay clasts. While these smectitic clasts may have had sufficient stability for fluvial transport in proximal streams, with greater transport distance the smectitic clasts would have dispersed more readily than kaolinite with the fine-grained smectite particles becoming part of the suspended load. Thus, the argillaceous bedload component of the fluvial sediments would have become enriched in kaolinite with longer transport distance. Coarser kaolinite clasts and particles would have been preferentially deposited on the floodplain while the dispersed smectite particles would have probably remained in suspension in the fresh water system and bypassed the floodplain in the suspended load to be carried into the marine basin.

Another possible mechanism contributing to the mature clay assemblage of distal Lower Ione sediments may have been related to the effects of the tropical climate and topographic variations on the distribution of soil types in source areas. The source areas shedding pedogenic detritus to the proximal streams near Nevada City were apparently dominated by kaolinitic soils judging by the clay assemblages of high order proximal fluvial deposits. However, these proximal sediment clay assemblages also reflect the contribution of other soil types with mixed clay assemblages (Table 2). These mixed-assemblage soils would have occurred in the region in response to local variations in topography and drainage conditions. As proximal Ione streams continued their westward flow to the basins, they would have traversed terrains of decreasing elevation and topographic relief. On these flatter terrains, Oxisols would have been more dominant on the landscape compared to the proximal areas of higher elevation. Conceivably, low order tributaries draining these lowland terrains closer to the basin may have transported kaolinitic pedogenic material of greater purity compared to the sediment assemblages of the high order trunk streams draining proximal areas. Thus, the purer kaolinitic assemblage of sediments eroded from the lowland terrains would have diluted the mixed clay assemblages in the high order trunk channels. By the time the Ione streams reached the basins, they would have carried pedogenic detritus of nearly monomineralic kaolinite composition.

Although these sediment maturing processes may have led to the unique quartz-kaolinite composition of distal Lower Ione sediments, in other respects, the composition of Lower Ione distal sediments differs significantly from some modern tropical river systems—notably, in the abundance of clay transported as bedload sediment. For example, data presented by Johnsson *et al.* (1991) show that detrital pedogenic clay clasts ("alterites") constitute up to only 3–4% of the composition of some Orinoco River basin sediments, or up to 7% if all pedogenic material (ferrugenous) is included. In contrast, pedogenic clay clasts constitute about 40–50% of the bulk volume of proximal Lower Ione sandstones and >50% of distal Lower Ione sandstones in the Ione area. The difference in the amount of detrital clay that was transported in the Eocene Ione verses the modern Orinoco fluvial system probably reflects another important controlling factor—position of the base level.

The implied effect of lowering the base level of a fluvial system is to increase both the potential and kinetic energy of the river. This results in an increase in both the erosive energy of the river and also the volume of sediment the river can transport. The Orinoco River system is currently in equilibrium with a high stand of sea level. Consequently, the stream gradient is low and the tropical soils in the river basin remain relatively stable.

Work by Johnsson and Stallard (1989) illustrates the significant difference in the volume of pedogenic material eroded and transported by streams with higher gradients and greater erosive energy. They reported that soils on Barro Colorado Island in Panama were developed under tropical climatic conditions—a mean annual temperature of 27°C and average annual rainfall of

260 cm with winter dry periods. These climatic parameters are similar to those that existed in the ancestral Sierras in the Early Tertiary. They found that the dominant mineral assemblage of soils developed on various terrains was influenced by both the tropical climate and the local topography with kaolinitic soils favored on flat terrains and smectitic soils on steeper slopes. They noted that soils on the steeper slopes never reached the maturity of those on flatter areas because of continual erosion and differing drainage conditions. The distribution of soils on this island resulting from the influence of climate and topography is probably analogous to the soils that developed on various terrains in the ancestral Sierras in the Early Tertiary.

The streams that erode the various soils on Barro Colorado Island all drain into Gatún Lake—the local base level. Johnsson and Stallard's (1989) maps show that streams traverse the maximum relief on the island (~120 m) over a horizontal distance of approximately 2–3 km. Therefore, conservative stream gradients are about 3–5%. Their data show that pedogenic material including clay and ferrugenous (lateritic) clasts constitutes 40–80% of the bedload sediment in these streams. These numbers are more in line with the volume of pedogenic bedload materials in Ione sediments. Gradients of Ione streams that flowed over the floodplains in proximal and distal areas were probably ~2% (MacGinitie, 1941)—less than those of streams on Barro Colorado Island but probably greater than gradients on the modern Orinoco River floodplain.

Thus, the position of the base level is probably the key factor that accounts for the disparity between the amount of pedogenic material in the Ione verses the modern Orinoco River sediments. MacGinitie (1941) believed that a significant lowering of the base level resulting in channel incision initiated the first or "erosive stage" of Ione fluvial system development (Fig. 14). This episode produced the V-shaped canyons in proximal areas of about 100 meters deep (MacGinitie, 1941) and cut the 200 meter deep Ione basin (Chapman and Bishop, 1975). During the "erosive stage", Ione streams with high stream gradients could have easily eroded through the lateritic soil cover and cut down into fresh bedrock resulting in an incongruent fluvial sediment mineral assemblage comprised of both fresh bedrock material and abundant kaolinite derived from local Oxisols. Pre-Ione fluvial sediments with a mineral assemblage matching this "erosive stage" description immediately underlie the Lower Ione sediments in the Ione basin (Pask and Turner, 1952).

MacGinitie (1941) attributed this base level lowering to regional uplift; however, Bateman and Wahrhaftig (1966) reported that the region of the ancestral Sierras during the early Eocene-Oligocene period was a time of tectonic quiescence. Haq *et al.* (1987) correlated a series of three significant sea level lowstands with the time of Ione fluvial activity (~50 Ma). One of these episodes probably caused the base level lowering event immediately prior to Lower Ione deposition described by MacGinitie (1941).

MacGinitie (1941) believed the thick sequence of mature Lower Ione sediments was deposited during an "aggradation stage" associated with a rise of the base level. This event caused the back-filling of the V-shaped channels with Lower Ione sediments. He reported that a major change in the composition of Lower Ione sediments occurred when the Ione rivers spilled over the top of the deep channel margins and began to laterally cut 2–3 mile wide benches on the surface of the surrounding topography (Fig. 14). Indeed, the Lower Ione channel deposits in proximal areas are characterized by sediments with abundant unweathered granitic and metamorphic rock fragments while the overlying Lower Ione bench deposits are dominated by highly weathered detrital material (MacGinitie, 1941; Yeend, 1974).

Although Ione streams lost kinetic energy during the aggradation stage because of lower stream gradients, they probably still had the ability to erode significant volumes of lateritic soil material by laterally undercutting soil cutbanks. MacGinitie (1941) reported that the most significant erosion of the surrounding lateritic soils occurred during this phase of the aggradation stage by Ione streams migrating laterally across the wide floodplain (Fig. 14). Figures 7 and 8 illustrate such an Ione fluvial/laterite erosional contact relationship. The incorporation of significant quantities of lateritic material by this mechanism probably accounts for the large volume of detrital sand-sized pedogenic kaolinite clasts in Lower Ione sediments.

MacGinitie (1941) observed the occurrence of mature soils developed on the bedrock flanks of the V-shaped channel adjacent to Lower Ione channel gravels in proximal areas and implied that these soils were lateritic (Fig. 3). Pask and Turner (1952) found similar mature soil development on the margins of the Ione basin in drill cores. These paleosols have not been classified but it is reasonable to assume that these channel margin soils are not Oxisols because of the sloping topography of the fluvial-cut canyons and because of the length of time required for the development of Oxisols. Nevertheless, the development of mature soils on the channel margins implies that a significant period of time separated the "erosive stage" from the "aggradation stage" of Ione fluvial development.

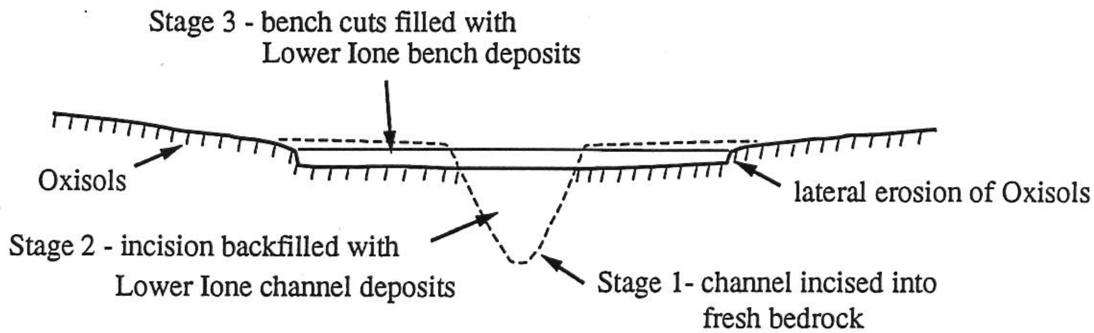


Figure 14

Sequence of Lower Ione fluvial development. Stage 1 and stages 2 and 3 represent MacGinitie's (1941) "erosive" and "aggradation stages", respectively.

Another possibility that could account for the time interval implied by the development of the channel margin soils is that the V-shaped channels were not cut by the Ione "erosive stage" but by a previous downcutting event immediately prior to Ione time. The fluvial deposits associated with an earlier downcutting event could have been subsequently removed by Ione fluvial scouring. Remnants of an earlier fluvial event could be represented by the "pre-Ione" sediments found by Pask and Turner (1952) in the bottom of the Ione basin in drill cores and those sandwiched between the lateritic soils and Ione fluvial deposits in outcrops north of Fresno near Friant (Palmer and Merrill, 1982).

Smectite in Ione Sediments

MacGinitie (1941) observed a distinct disconformity in proximal areas separating the mature kaolinitic sediments of the Lower Ione from immature sediments of the overlying Upper Ione. He speculated that either a change in the rate of erosion or a climatic change might account for the different sediment composition of the Upper Ione (Fig. 15). He proposed that a subsequent base level lowering event with consequent fluvial scouring of fresh bedrock material probably caused a change in the composition of Upper Ione sediments. If true, the latter of three sea level lowstands at ~50 Ma identified by Haq *et al.* (1987) may correlate with this event. The study of the smectitic Ione sediments at the Manzanita site shows that a downcutting episode may have caused the removal of the upper kaolinitic horizons of regional soils leaving underlying soil horizons with smectitic clay assemblages exposed at the surface.

Evidence also indicates that a major tempering in the global climate occurred commencing at the early/middle Eocene boundary (Miller, 1991). The resulting change in the severity of surface weathering was probably an additional factor involved in producing the immature Upper Ione sediment composition.

Immature sandstones in the Nevada City area with abundant feldspar and biotite, matching the criteria of Upper Ione sediments, possess a dominantly smectitic clay assemblage. The highly crystalline smectite occurring in these Upper Ione sandstones was probably the result of the smectitization of mica in source area soils under a more moderate climate compared to the early Eocene climate. Smectitic mudstones are interbedded with the proximal Upper Ione sandstones; however, smectite in the mudstone beds is not the highly crystalline smectite similar to that contained in the enveloping sandstones. The proximal Upper Ione sediment samples came from a position in the fluvial system that was probably relatively close to the sediment source. Consequently, the smectitized mica grains probably had not abraded sufficiently at that phase of fluvial transport to have contributed much coarsely crystalline smectite material to the suspended sediment load.

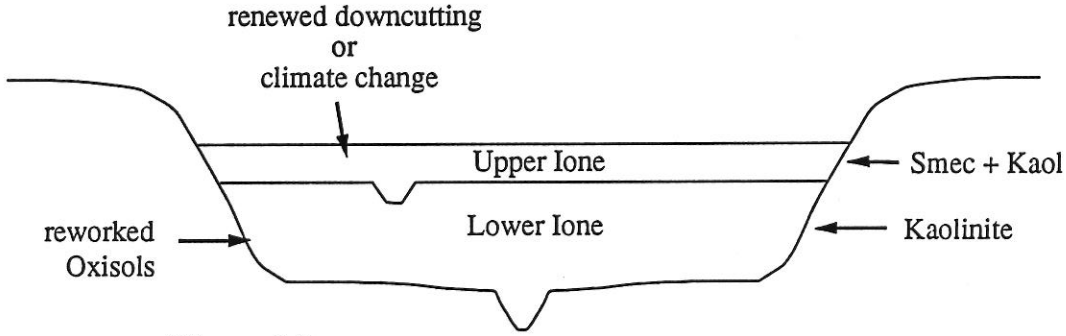


Figure 15
Relationship of Lower Ione and Upper Ione sediments.

The increase in the amount of coarsely crystalline smectite in Ione mudstone beds toward the top of the section both at Lincoln and Ione may reflect the transition from the dominantly kaolinitic clay assemblages typical of Lower Ione sediments to the mixed smectite/kaolinite assemblages of Upper Ione sediments. If smectitized mica also occurred in the Upper Ione fluvial systems feeding the basin at Ione, then a possible explanation for its appearance in the mudstone beds in the distal reaches of the depositional system could be that the longer transport distance to Ione basins may have caused the disaggregation or abrasion of smectitized mica grains. Consequently, a moderate amount of abraded coarsely crystalline smectite could have become part of the suspended sediment load by the time the sediments reached the distal reaches of Ione fluvial systems. The upward increase in the amount of coarsely crystalline smectite in the Bacon pit mudstones at Ione may be indicative of a transition from kaolinized mica to smectitized mica in Ione sediments. Ultimately, this scenario implies that the occurrence of the smectite in the mudstones at Lincoln and Ione is a signature of a regional climate change that led to a change in the dominant weathering regime affecting Ione source areas.

Pedogenic Sediment Classification

There are probably few preserved ancient examples of fluvial sediments analogous to Ione sandstones that are comprised of such a large volume of pedogenic material. Certainly few are described in the literature. Consequently, the classification of sandstones comprised largely of highly weathered soil debris has not been adequately addressed. In one classification scheme (Williams *et al.*, 1954; Dott, 1964), the argillaceous Ione sandstones might be classified as "quartz wackes" since clay constitutes >10% by volume of Ione sediments. However, the kaolinite in Ione sandstones is largely in the form of detrital pedogenic clay clasts that were squashed and formed pseudomatrix and, technically, the kaolinite in Ione sandstones is not matrix clay. Therefore, Ione sandstones should be classified in accordance with 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 derived from weathering profiles in source areas. Therefore, the clay clasts in Ione sediments should be recognized for what they really are—"pedogenic" clay aggregates.

"Pedogenic clay aggregates" is a somewhat cumbersome and laborious term to refer to a single component in clastic rocks and does not fit well with established clastics nomenclature. 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. "Pedogenic rock fragments" is an alternative term to "pedoliths" but as the altered soil materials are no longer rock and a precedent has been set for the use of "pedoliths", the latter appears to be more appropriate.

Pedoliths (or Pedogenic RF's) would be one component of the lithic compositional triangle for Ione sediments (Fig. 16b). As pedoliths constitute the majority of lithic materials in Ione sandstones, then "pedoliths" would also form the lower right component of the Folk sandstone composition triangle (Fig. 16a). In this classification scheme, both high order proximal and distal Lower Ione sandstones plot in the "pedolitharenite" (or alternatively, "pedarenite") category (Fig. 13). "Pedolitharenite" or "pedarenite" are terms that succinctly describe sandstones with a significant component of detrital pedogenic material and fit well with current sandstone classification convention.

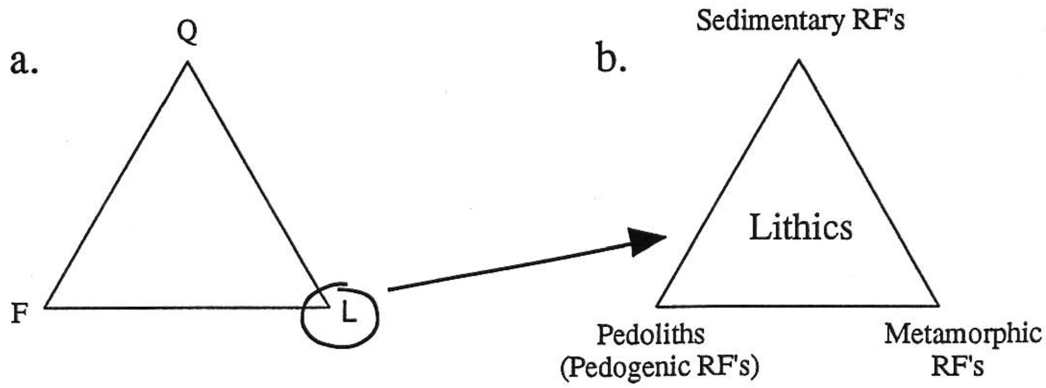


Figure 16.
Components of a Folk-based (1974) classification scheme for Ione sediments.

CONCLUSIONS

Petrographic evidence presented in this study shows that kaolinite in Ione Fm. sediments meets the criteria of Dickinson (1970), and Wilson and Pittman (1977) to be classified as detrital clay in the form argillaceous lithic aggregates that were deformed by compaction and formed pseudomatrix. Ione kaolinite possesses diagnostic pedogenic micromorphologies providing additional evidence that Ione kaolinite was derived from the erosion of Oxisols and related kaolinitic soils. Sufficient differences exist between pedogenic and authigenic kaolinite micromorphologies that the two can be reliably distinguished in sandstones.

The development of deep weathering profiles such as the Manzanita Oxisol require extremely long periods of chemical weathering under warm-humid climatic conditions accompanied by a stable continental setting. These prerequisites existed throughout high latitudes of North America in the Early Tertiary and kaolinitic tropical soils probably mantled large areas of the ancestral Sierras. A significant base level lowering event, probably associated with a sea level lowstand, initiated the massive erosion of the widespread and thick kaolinitic soils. Oxisols and related chemically weathered soils have the potential to shed large volumes of kaolinitic detritus to fluvial systems in the form of sand-sized clay aggregates. Pedogenic amorphous siliceous cements and the inherent nature of the pedogenic aggregate microfabric apparently enhanced the stability of kaolinitic clay aggregates incorporated into Ione fluvial sediments.

Petrographic evidence shows that kaolinite in Ione sediments is primarily in the form of pedogenic clay aggregates, kaolinized mica, and disaggregated detrital mud. The stable kaolinite clasts were transported in the Ione fluvial system as bedload sediment and the fluvial flow regime was apparently a major controlling factor determining the morphology and abundance of kaolinite clasts in Ione sediments. Consequently, detrital clay aggregates, kaolinized mica, quartz, feldspar, and heavy minerals were all hydrodynamically equivalent in well sorted Ione fluvial sediments.

A sediment maturation process that operates in modern tropical river systems was probably an important factor in determining the unique composition of Ione sediments. Petrographic evidence shows that post-depositional weathering of proximal Ione sediments in temporary storage on the floodplain caused the dissolution of weatherable minerals including feldspar. Consequently, reworking of these sediments by migrating fluvial channels would have yielded sediment with greater compositional maturity. Continual infusion of compositionally mature quartzose sand as a result of this mechanism operating the entire length of the stream course probably explains why distal Ione sediments contain little more than trace amounts of feldspar and other weatherable minerals.

The 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 based on their physical appearance has been grossly overestimated. Petrographic evidence indicates that these paleosols are not indicative of deep chemical weathering. The effects of post-depositional weathering on underlying Ione sediments were largely superficial—only affecting the upper few meters of sediments exposed at the paleosurface. The oxidation of iron chelated with organo-siliceous cements in the clay sediments 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. Consequently, petrographic evidence does not support the notion of a significant occurrence of authigenic kaolinite in the Ione Fm. as a result of post-depositional weathering.

The kaolinite and quartz mineral suite of the Lower Ione fluvial deposits is labeled "unique" by modern standards. However, it is clear that fluvial deposits of this composition should be the expected result of a number of geological factors which do not all coexist today, namely—a long period of chemical weathering contemporaneous with stable continental conditions producing kaolinitic tropical soils of regional extent; a significant sea level lowstand leading to significant erosion and transport of tropical soil material by fluvial systems; and the operation of a tropical compositional maturing process that modifies the fluvial sediment composition through post-depositional weathering and sediment reworking. These geological factors probably coincided during the early Eocene in the ancestral Sierras in California as well as in other parts of the world at various times in the geologic past. During such times, river systems similar to the Ione transporting massive volumes of kaolinitic detritus were probably not unique and "rivers of kaolinite" may not have been uncommon in many areas of the world.

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