

To Prof. Sengupta
with best regards
Sarbari

Fe-illites in a Proterozoic Deep Marine Slope Deposit in the Penganga Group of the Pranhita Godavari Valley: Their Origin and Environmental Significance¹

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ABSTRACT

Ferric illite (Fe-illite) developed extensively in a siliciclastic submarine fan sequence within a lime-mud succession in the Proterozoic Penganga Group at Adilabad, South India. The minerals formed as *de novo* by preferentially replacing high-K minerals like alkali feldspar and mica. It is compositionally intermediate between glauconite and illite in a continuously varying chemical spectrum. The mineral exhibits an R1 or R3 type stacking sequence, with low (<10%) interlayering of illite and smectite (I/S). All the analyzed grains are characterized by high potash content, and it has been inferred that the maturity is dictated by high a_k^* in the microenvironment. This occurrence strongly calls into question the environmental significance that has so far been attributed to glauconitic minerals.

Introduction

Fe-illite is a green, authigenic mineral structurally, morphologically, and optically similar to glauconite. It is considered to be a characteristic of saline condition in lacustrine and lagoonal environments (Keller 1958; Parry and Reeves 1966; Porrenga 1968; Kossovskaya and Drits 1970). It is also reported from fluvial depositional settings and tidal flat settings (Brookfield and Sahni 1987; Dasgupta et al. 1990). There is no record of the mineral from marine environments. Glauconite, on the other hand, has been almost universally accepted as a sensitive indicator of low sedimentation rates in marine environments.

In the present paper we describe authigenic Fe-illites from a submarine fan sequence in the Proterozoic Penganga Group of the Pranhita-Godavari Valley basin (P. G. Valley basin), where the mineral occurs in diverse morphologies and on different substrates along with glauconite. We discuss structural and chemical characteristics of the mineral, its relationship with glauconite, and its environmental implication.

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Definition of Fe-illite

Fe-illite is an iron-rich constituent of the illite-smectite series and is compositionally intermediate between glauconite and illite (Odin and Matter 1981; Odom 1984). Odin and Matter (1981) maintain that there is a distinct compositional gap between glauconites and illites at about 10–15% Fe₂O₃ and excluded Fe-illite from their family of glauconitic minerals. The compositional continuity between Fe-illite and glauconite, however, is reported by Kossovskaya and Drits (1970) and Dasgupta et al. (1990), who considered Fe-illite as a "glauconitic mineral." Strickler and Ferrell (1990) used the octahedral Fe to Al^{VI} ratio to identify different "glauconitic minerals" whereas Kossovskaya and Drits (1970) classified the minerals on the basis of a ferruginicity index, Fe³⁺/Fe³⁺ + Al^{VI}. In the present work, we have followed the classification scheme proposed by Kossovskaya and Drits (1970). Unless specified, the term "glauconitic minerals" denotes Fe-illite, illitic glauconite, and glauconite.

Analytical Methods

The Fe-illites were analyzed by optical microscope, X-ray powder diffractometer, and electron micro-

probe. Medium sand-sized pellets without any microscopically visible contaminations were hand-picked, powdered, and further disaggregated ultrasonically. Air dried and ethylene glycol solvated samples were run on a MXP3VA X-ray diffractometer (MAC Science Co.) at 40 kv, 20mA using Cu-K α (with monochromator) radiation at a scanning speed of 2° per min (Time constant 2.5 sec; slits 1-1-0.30).

The composition of the minerals was determined by using a JEOL-JXA733 Electron Probe Microanalyzer operated at 15 kv accelerating voltage and 1–2 μ m electron beam diameter. Synthetic orthoclase (K, Al), wollastonite (Ca, Si), periclase (Mg), albite (Na), and hematite (Fe) were used as standards. The EPMA data were corrected by the ZAF method. The analyses were done in the Instrumental Centre for Chemical Analysis, Hiroshima University.

Geological Setting and Depositional Environments of the Glauconitic Sandstones in the Pranhita Godavari Valley

The Penganga Group forms a part of the Proterozoic Godavari Supergroup of the P. G. Valley basin, South India and is best exposed around Adilabad in the northwestern part of the basin (figure 1). The Penganga Group unconformably overlies the basement granite and consists of three formations, which in the ascending order are: a shallow marine subarkosic sandstone (Pranhita Sandstone), a deep marine carbonate ramp (Chanda Limestone), and a deep water shale sequence (Sat Nala Shale) (table 1) (Chaudhuri et al 1989; Mukhopadhyay et al. 1997).

The Pranhita Sandstone consists primarily of profusely cross-bedded subarkosic sandstone, deposited in near-shore environments. The sandstone is overlain by the Chanda Limestone through a thin interval of shale. The Chanda Limestone consists almost entirely of very well bedded and laminated lime-mudstone, which includes in its lower and middle parts a large number of thin sheets of intraformational limeclast conglomerates and calcarenites of debris flow and turbidite origin. The mass flow-bearing intervals of the limestone have been interpreted as slope deposits (Bose and Sarkar 1991; Bandopadhyay 1996; Mukhopadhyay et al. 1997), and the underlying shale represents the shelf to slope transition zone.

A lenticular body of glauconitic sandstone occurs within the lowest few meters of the lime-mudstone. The glauconitic sandstone consists of two major facies. The dominant facies (F1) consists of thin plane-parallel laminated to ripple lami-

nated, medium- to fine-grained, friable green sandstone with high mud matrix. The subordinate facies (F2) occurs as thick, massive bedded (figure 2), light green, carbonate-cemented, highly indurated medium- to coarse-grained sandstone. The F2 beds are slightly lenticular with concave up or irregular basal surfaces and flat upper surfaces. The maximum thickness of an F2 bed is about 1.5 m, with an outcrop length of about 12 m. The sandstone is ungraded but contains a few floating clasts of limestone and shale. The largest clast is about 20 cm long. The clasts are commonly concentrated in the upper part of the beds (figure 2) and impart an appearance of coarse tail grading (Middleton and Hampton 1973; Bull 1977). Fe-illite constitutes about 10 to 12% of the sandstone but is conspicuously absent in the associated limestones or in the underlying Pranhita sandstone.

The morphology of the glauconitic sandstone lens and the attributes of the F1 and F2 beds are consistent with fan deposits (Piper 1970; Mutti and Ricci Lucci 1972; Walker 1978), fed by small canyons incised into the shale-carbonate slope (also see Bandopadhyay 1996). Dominance of plane laminated and ripple laminated components advocate mid- to outer fan environments. The lime-mudstone, which hosts the sandstone fan, is brown in color, indicating that the whole assemblage was deposited within the oxic zone.

Petrography

Fe-illite occurs primarily as round or subround peloids (figure 3a), stumpy irregular grains, or as partial replacements of detrital feldspar grains (figure 3b) and mica flakes (figure 3a). It also occurs as rims on quartz grains, as thin film between detrital grains (figure 3c), and as finely disseminated specks or films within the matrix. Though rare, broken peloids of Fe-illite are also present.

Most of the peloids are circular or capsule-shaped (figure 3a and d) and are generally smooth. Many peloids show parallel, polygonal, or reticulate internal cracks (figure 3e). Several are mammillated and exhibit lobes with narrow necks, delicately attached to a central point. Stumpy, irregular grains are characterized by a well-preserved single set of very closely spaced cleavage (figure 3a). In the incipient stage of replacement Fe-illite occurs as small discontinuous blebs (figure 3b) or along cleavages or fractures of the precursor grains, whereas in the advanced stage the major part or almost the whole of the host grains (figure 3f) has been replaced. In a few peloids tiny relicts of host engulfed within Fe-illite betray the precursor min-

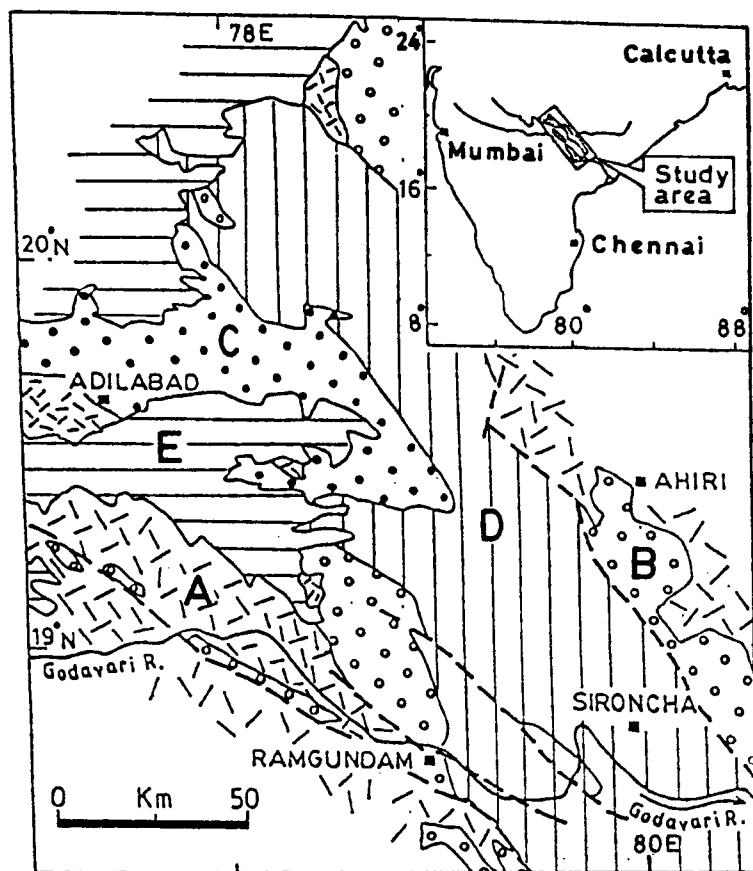


Figure 1. Geological map of the northwest part of Pranhita Godavari Valley, South India. A: Basement complex; B: Undifferentiated Proterozoics; C: Penganga Group (Proterozoic); D: Gondwana Supergroup (Up. Paleozoic-Mesozoic) and E: Deccan Trap (Up. Cretaceous-Lr. Tertiary). Modified after Chaudhuri and Chanda (1991).

Table 1. Stratigraphic succession of the Penganga Group around Adilabad, Andhra Pradesh

Formations	Lithology	Internal structure
Deccan Traps		
—Unconformity—		
Penganga Group:		
Sat Nala Shale	Reddish brown shale	Very persistent thin laminations
Chanda Limestone	Micritic limestone with thin shale interbeds. Glauconitic sandstone, Manganese oxide ore, Bedded chert and dolomite are minor constituents	Thin persistent lamination; varve-like alternation of limestone and shale; limeclast conglomerates, either chaotic or graded-bedded; massive beds in coarse-grained glauconitic sandstone with large limeclasts
Pranhita Sandstone	Coarse- to medium-grained quartzose/subarkosic sandstone with subordinate amount of greenish mudstone	Cross-bedding; ripple marks
—Unconformity—		
Basement Complex (Undifferentiated)		

Source. Chadhuri et al. 1989.



Figure 2. A massive ungraded bed of medium- to coarse-grained glauconitic sandstone. A few floating clasts concentrated in the upper part of the bed. Thickness of the bed decreases toward the right of the photo.

eralogy of the peloids (figure 3f). Within the matrix it normally occurs in highly localized irregular patches.

Under plane polarized light the minerals in most of the complete peloids and highly replaced grains are grass green and yellowish or brownish green in only a few. Under cross nichols Fe-illite in most of the peloids shows first-order interference color, either gray or gray masked by brown. A few stumpy grains with one perfect cleavage set show higher-order variegated interference color, which apparently reflects the inherited higher birefringence of the precursor mica flakes.

Most of the peloids show aggregate extinction characterized by small platelets, whereas a few show pinpoint extinction that consists of small granular internal constituents. In the peloids with fibrous texture, the fibers are often oriented in two directions, presumably representing two sets of cleavages, or are aligned perpendicular to narrow parallel strips, representing twin laminae of feldspars (cf. Chaudhuri et al. 1994). In rare instances, the cryptocrystalline fibrous structures show spherulitic arrangement. Several peloids show patchy development of randomly oriented platelets and granular structure.

Chemical Characteristics

The chemical composition is given in table 2 (which is available, with table 3 from *The Journal of Geology* upon request). The structural composition recalculated from the microprobe data, their tetrahedral and octahedral charges, interlayer charge as well as the ferruginicity index (cf. Kossov-

skaya and Drits 1970) are given in table 3. The chemical compositions were recast into structural formulas on the basis of a cell with an anion content of $O_{10}(OH)_2$ (Manghnani and Hower 1964).

Most of the analyzed grains, irrespective of the substrate or degree of replacement can be classified as Fe-illite. There are a few grains of glauconite. A few grains show intermediate characteristics and may be classified as "illitic glauconite" (cf. Kossovskaya and Drits 1970), where tetrahedral charge is equal to or greater than octahedral charge but the ferruginicity index is well within the glauconite field (table 3).

X-ray Diffraction Pattern

The XRD tracings (figure 4) are analogous to the computer-simulated patterns for natural glauconite and illite-smectite series with <10% interlayered smectite described by Thompson and Hower (1975). Well-defined 112 and $11\bar{2}$ reflection in the random-oriented sample (figure 4a), and sharp diffraction at 10.1A, 4.5A, and 3.3A in preferred-oriented air-dried (figure 4b) and glycol-solvated samples (figure 4c) point to a well-ordered R1 or R3 type stacking sequence of glauconite (Bentor and Kastner 1965; Moore and Reynolds 1997). Low illite/smectite interlayering is also indicated by the similar pattern in oriented air-dried and ethylene-glycolated samples (Thompson and Hower 1975).

Origin of Fe-illite

Our data show that Fe_2O_3 content in the green minerals varies between 3.5 and 12% (figure 5), and a large number of analyzed grains fall in the 10–12% Fe_2O_3 range, indicating a compositional continuity between illitic and glauconitic minerals. Close association of glauconite, Fe-illite, illitic glauconite, and illite on a microscopic scale, their similar mode of occurrence, similar crystal structure, and the compositional continuity between them collectively suggest that the minerals developed as a group of genetically related authigenic phases. The compositional continuity between illitic and glauconitic phases is a possible indicator of the development of glauconite from illitic material by progressive incorporation of iron. The X-ray graph shows that the Fe-illite has a dioctahedral micaceous structure, and we therefore conclude that the transformation occurred within the micaceous structure.

Chemical transformation within a micaceous structure, however, does not dictate that an illite would always be the starting point for the mineral-

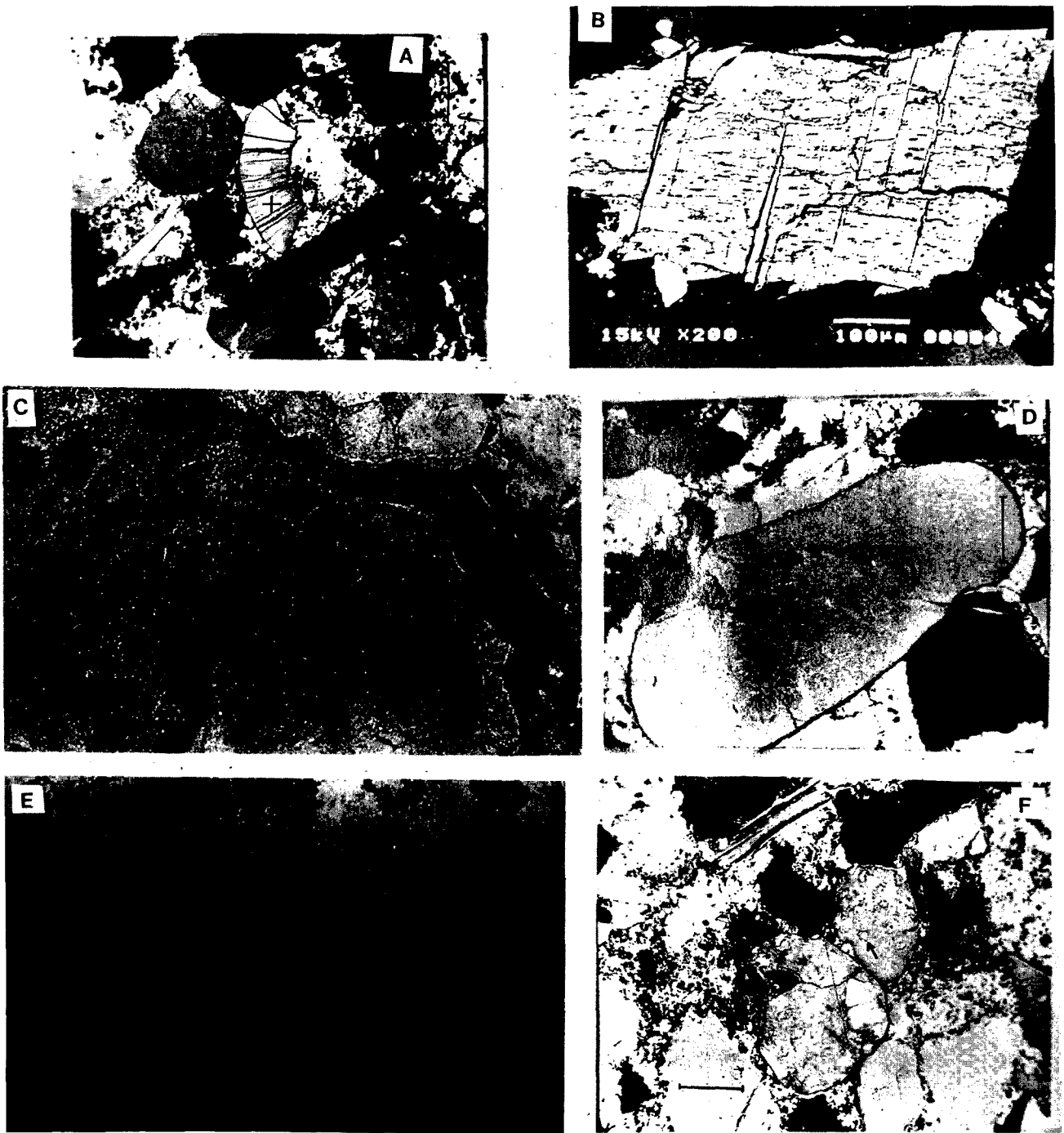


Figure 3. *a.* Back-scatter electron image showing occurrence of Fe-illite as round peloids (cross) and a fan-shaped stumpy grain with one set of the well-preserved cleavage of the precursor mica flake (plus). Bar = 100 μm . *b.* Back-scatter electron image of minor blebs and stringers of glauconitic minerals along the cleavages and cracks within a feldspar grain. Bar = 100 μm . *c.* Photomicrograph (plane polarized light) of Fe-illite (arrow) in the area between two quartz grains. Bar = 0.011 mm. *d.* Back-scatter electron image of well-rounded capsule-shaped peloid of Fe-illite. Note presence of cracks. Bar = 100 μm . *e.* Photomicrograph (plane polarized light) of a Fe-illite peloid with internal polygonal cracks. Bar = 0.17 mm. *f.* Back-scatter electron image of a peloid in a highly advanced stage of replacement by Fe-illite with small remnants of feldspar (arrow). Bar = 100 μm .

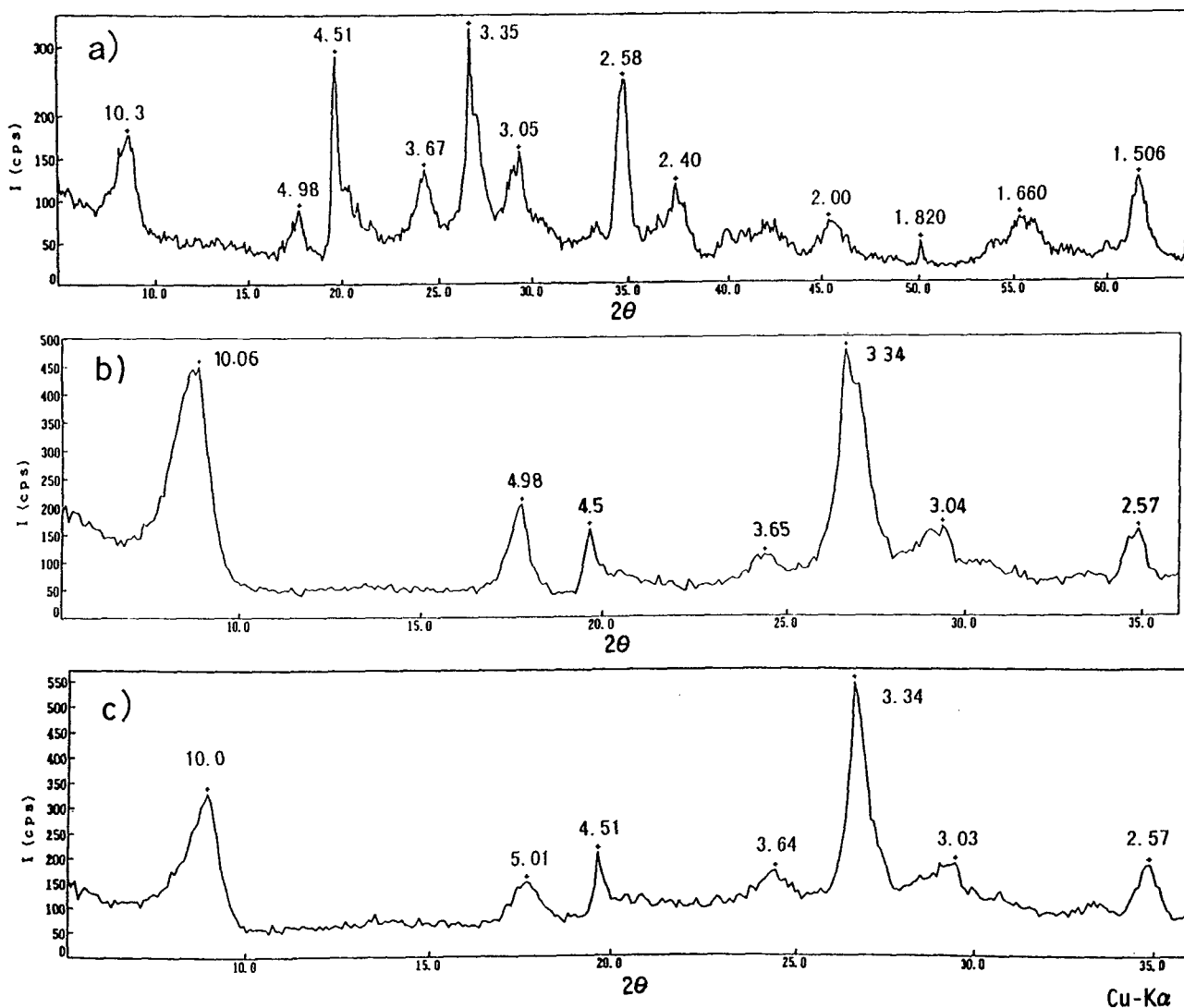


Figure 4. X-ray powder diffraction patterns of glauconitic minerals. *a.* Tracing of random-oriented sample; *b.* tracing of preferred-oriented, air-dried sample; and *c.* tracing of preferred-oriented, glycol-solvated sample.

ogical changes as suggested by Burst (1958*a*, 1958*b*) or Hower (1961). Presence of the glauconitic minerals as rims or growth of the minerals by replacement of different detrital grains strongly points to their authigenic growth (cf. Kossovskaya and Drits 1970; Odin and Matter 1981; Ireland et al. 1983; Dasgupta et al. 1990). Authigenic growth of illite in sedimentary environments has recently been demonstrated by Hugget (1995). The composition of the initial precipitate in the diagenetic environment could vary depending on the composition of the pore water.

Detrital grains of high-K minerals, like alkali feldspar and mica, are the most preferred hosts for the growth of glauconitic minerals, and the association is a strong indication of a genetic relationship

between them. Dissolution of alkali feldspar and detrital mica in a diagenetic environment is a potential source for K in the pore water (Hower 1961; Hugget 1995), and the K may participate in the authigenic feldspar overgrowths (Stablein and Dapples 1977) and illite (Hugget 1995). We propose that extensive dissolution of feldspar and mica in the early diagenetic environments resulted in supersaturation of the pore water in ions like Si^{4+} , Al^{3+} , K^+ , and Mg^{2+} . The mineral reactions involving the detrital grains and the supersaturated pore water resulted in the growth of authigenic illite, Fe-illite, and glauconite, depending on the availability of iron. We therefore suggest that the glauconitic minerals precipitated as well-ordered high-K phases under high a_{K^+} in the microenvironment (cf. Odom

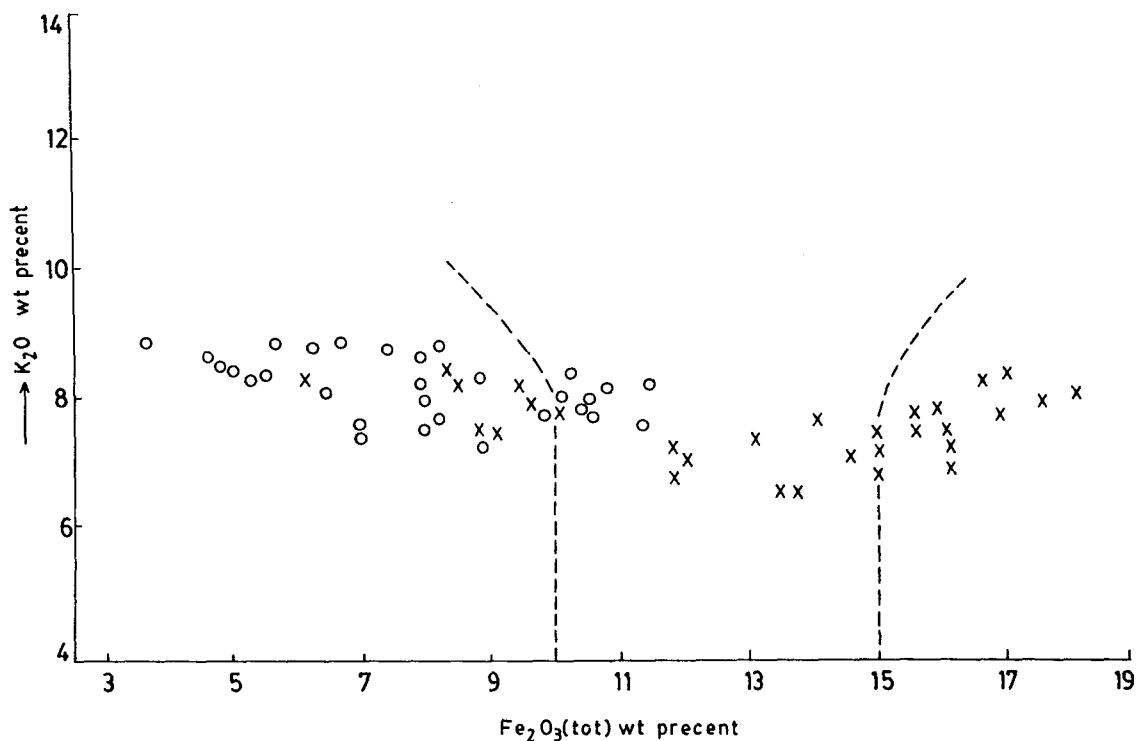


Figure 5. Plots of K_2O vs. Fe_2O_3 (total) showing continuum in composition between illitic and glauconitic mineral families. Data from table 1 (open circles) and from Dasgupta et al. (1990) (crosses). Values between about 10–15% Fe_2O_3 suggest the presence of a mineralogical transition between illitic and glauconitic minerals.

1984; Dasgupta et al. 1990; Hugget 1995). Our limited data also indicates that the high variation in the Mg^{2+} content is partly controlled by substrate composition (see table 2). Glauconitic minerals developed on biotite have persistently higher Mg^{2+} than those formed on other substrates.

Environmental Significance of Fe-illite

Fe-illite has been reported primarily from lacustrine and lagoonal environments, and a close association with dolomitic marl or gypsum has been noted (Jung 1954; Keller 1958; Parry and Reeves 1966; Porrenga 1968; Kossovskaya and Drits 1970). Dasgupta et al. (1990) reported Fe-illite from fluvial arkosic sandstones without any specific association of evaporitic minerals. Dasgupta et al. (1990) also reported Fe-illite from a Proterozoic intertidal sandstone sequence, where it occurred in close association with glauconite. They suggested that the mineral formed under the influence of fresh water in a zone of intermixing with marine water. High-alumina glaucony or glauconitic minerals compositionally similar to Fe-illites have been described from shallow marine environments within a bathy-

metric range of about 50 m by Berg-Madsen (1983) and Strickler and Ferrell (1990).

Our report from the P.G. Valley further extends the environmental limit of Fe-illite to deep marine slope and base of slope environments. It becomes evident that origin of Fe-illite is not constrained by hypersalinity or fresh water activity, and the mineral may develop in diverse environments. Its occurrence in diverse environments further suggests that the origin of Fe-illite or glauconitic mineral is not constrained by macroenvironments. The compositional variations, on the other hand, appear to be closely related to the compositions of the substrates that host the Fe-illites and the pore fluid composition.

Occurrence of Fe-illite in continental, shallow marine, and deep marine environments, its coexistence with glauconites in different basins, and the compositional continuity between the two phases clearly call into question the environmental significance so far attributed to them. Rather than forming in mutually exclusive marine and nonmarine environments (cf. Kossovskaya and Drits 1970; Odin and Matter 1981), the authigenic phases could develop as illite, Fe-illite, and glauconite in the

same environment, depending on the availability of required ions and microscale variation in chemical parameters within the enclosing sediments.

Summary and Conclusions

1. Fe-illites developed in the deep marine slope and base of slope setting in the Proterozoic Chanda Limestone by replacing detrital grains, as well as clayey matrix, preferentially the high-K minerals like alkali feldspar and mica. The minerals also formed as thin films coating detrital grains such as quartz. Different substrate grains showed different degrees of replacement; composition of the substrates of complete peloids is betrayed by tiny remnants of the precursor mineral.

2. Fe-illite occurs in close association with illite, illitic glauconite, and glauconite, in a continuously varying chemical spectrum from illite to glauconite without any break. Different minerals are classified on the basis of ferruginicity index and also tetrahedral and octahedral charges.

3. The minerals formed *de novo* as high-K phases replacing or on different kinds of substrates within a high a_k^+ microenvironment created by dissolution

of alkali feldspar and mica. The degree of diagenetic compositional transformation was dictated by availability of required ions, particularly of iron and chemical potential of the constituent ions in pore fluids.

4. The compositional variations in the glauconitic minerals appear to be dictated by microchemical environments rather than macroenvironments. Further, occurrence of Fe-illite in wide-ranging environments in close association with glauconite, or the proposed origin of the minerals, call into question the environmental significance that has been attributed to these authigenic minerals over the years.

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