Physical Sciences

Identification of Kaolin Polytypes and other Minerals in Sediments of Thar Coal Field, Sindh, Pakistan

Muhammed Atique Ahmed Baig* and Mujeeb Ahmad

Department of Geology, University of Karachi, Karachi - 75270, Pakistan

Abstract. Study of the core samples of powder and clay (< 2 μ) fraction grain size from coal field of Thar, Sindh, Pakistan, for the mineral composition, kaolinization processes and environments of the deposition, indicated both types of kaolinite i.e. well crystalline and degraded, as the main constituents in both the samples. Quartz and anatase were in sub-ordinate amounts in random powder, and dickite in clay fraction. Authigenic and degraded, both types of kaolinite, were present in the sediment. Dickite showed its presence in restricted samples, whereas anatase (TiO_2), detrital of authigenic origin, were present in the whole-rock samples. It is inferred that leaching of kaolinite and sufficient amount of titanium from the Tharparkar granite produced authigenic anatase and some amount of detrital anatase was contributed by the weathering of Nagarparkar granite. Presence of detrital minerals i.e. quartz, kaolinite, anatase and also the iron oxide, suggest a near-shore deposition, under reducing and micro-oxidizing environments.

Keywords: kaolin polytypes, dickite, anatase, nacrite, Thar coal field

Introduction

The sub-surface kaolin deposits in the Thar coal basin became popular after the discovery of huge deposits of coal in the Thar desert during 1993-94. Thar desert is situated in a depression, bounded between the mountain belt of Hyderabad Arch to its west and the Indian shield towards its east (Jones, 1960). Fig. 1 shows the locations of the Thar coal basin and the bore holes. The kaolin deposits associated with alluvium as well as with the Nagarparkar granite complex of precambrian age, which form a structural platform are shown in Fig. 2. Two types of kaolin i.e. authigenic and detrital, have been noticed in the borehole samples. Recycled kaolinite of an average thickness of 3-5 meter is present above and in between the coal seams of the paleocene age and also in the bottom of the sediments.

The present study was initiated with the aim to gain some insight regarding the mineral composition of the whole-rock and clay (< 2 μ) fractions grain size of these sediments and also to identify the polytypes i.e. nacrite, dickite and halloysite of kaolinite family and to trace their modes of formation. Attempt has also been made to explain the processes of kaolinization, which existed in the basin of deposition.

Geologist from the Geological Survey of Pakistan in collaboration with the Geological Survey of USA worked in the Thar desert, but their work was mainly related to different types of surveys, including geophysical surveys to search for the sweet water resources for the population of Tharparkar area.

Fassett and Durrani (1994) compiled a comprehensive report regarding the geology and coal resources of Tharparkar coal field. In this report they have correlated the subsurface geology of the Tharparkar area, however information regarding mineral composition of the sediments is missing. Ahmed and Zaigham (1993) described the seismostratigraphy and the basement configuration in relation to coal bearing horizon in the Tharparkar desert. Margane (1991) published information regarding the paleoclimate and groundwater recharge during the past 30,000 years in Cholistan in Tharparkar area. SanFilipo *et al.,* 1992, described the potential for the occurrence of thick lignitic coal deposits in Tharparkar desert and documented the exploratory results from Thar desert, Lakhra and Indus south plain areas, from Sindh Province (SanFilipo *et al.,* 1994). Thomas (1994) published the data from the drilling activities in the Thar desert. Tabinda and Fatmi (1995) carried out preliminary petrological and sedimentological studies of the selected core samples of Thar coal basin.

Abdallah *et al.* (1997), were the first who studied the detailed mineralogy of the clay fraction (< 2 μ) and the whole-rock samples and geochemistry of the core samples of two bore-holes i.e. STP-11 and STP-13 from the Tharparkar coal basin. They identified the clay mineral species by the X-ray diffraction method. Based on their mineralogical and geochemical findings, they concluded that the sediments were deposited under shallow-marine conditions. However, the clay mineral composition of the sediments of the area were lacking in the study. In the present research paper not only the clay mineral composition of the studied sediments has been described,

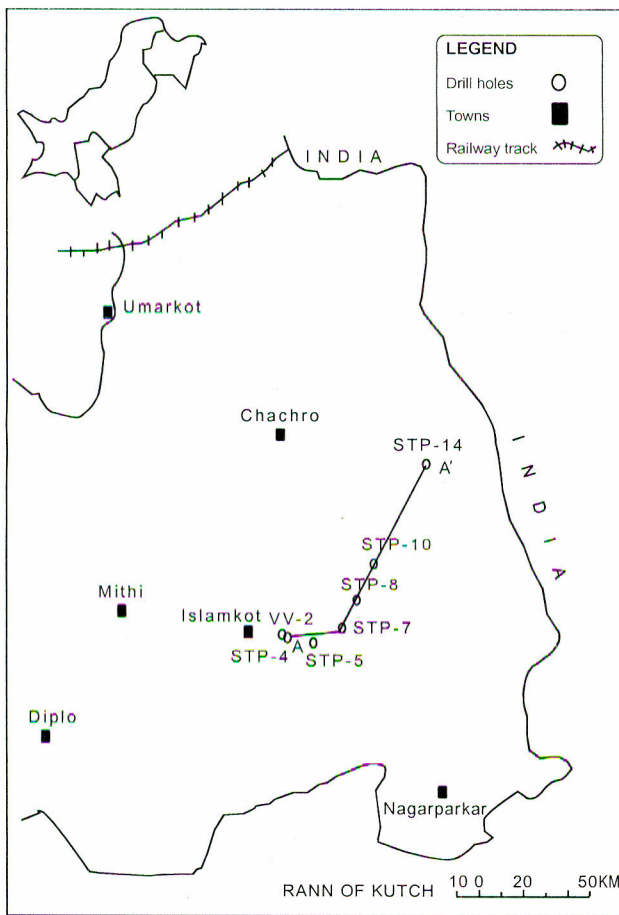*Author for correspondence; E-mail: atique1941@yahoo.com

but, for the first time, the polytypes of kaolinite e.g. dickite, nackrite and halloysite have been identified and the mode of formation of the clay minerals and the kaolin polytypes have been traced, which is a significant contribution to the clay mineralogy of the Tharparkar coal basin.

Materials and Methods

Ten core samples from the six cores of the Thar coal basin were selected from the Geological Survey of Pakistan, Karachi. Fig. 1 shows the location of bore holes. Depth of bore holes and the status of each sample are shown in Table 1.

Table 1. Drill hole number, depth of core samples taken and the status of kaolin sampling in bore holes, Thar coal basin

Sample	Drill hole no.	Depth (m)	Description
T-1	STP-7	134.74/134.94	Kaolin above coal
T-2	STP-8	192.17/194.12	Kaolin below coal
T-3	STP-10	172.12/175.26	Kaolin above coal
T-4	STP-4	133.90/134.00	Kaolin above coal
T-5	STP-5	138.60/138.69	Kaolin above coal
T-6	TP-14	212.17/212.80	Kaolin above coal
T-7	VV-02	214.25/214.35	Kaolin above coal
T-8	STP-4	136.60/136.80	Kaolin above coal
T-9	STP-14	243.30/243.80	Kaolin below coal
T-10	STP-14	272.70/273.00	Kaolin above coal

Fig. 1. Location map of Thar coal basin, Sindh, indicating section line AA′ along drill holes TP and STP.
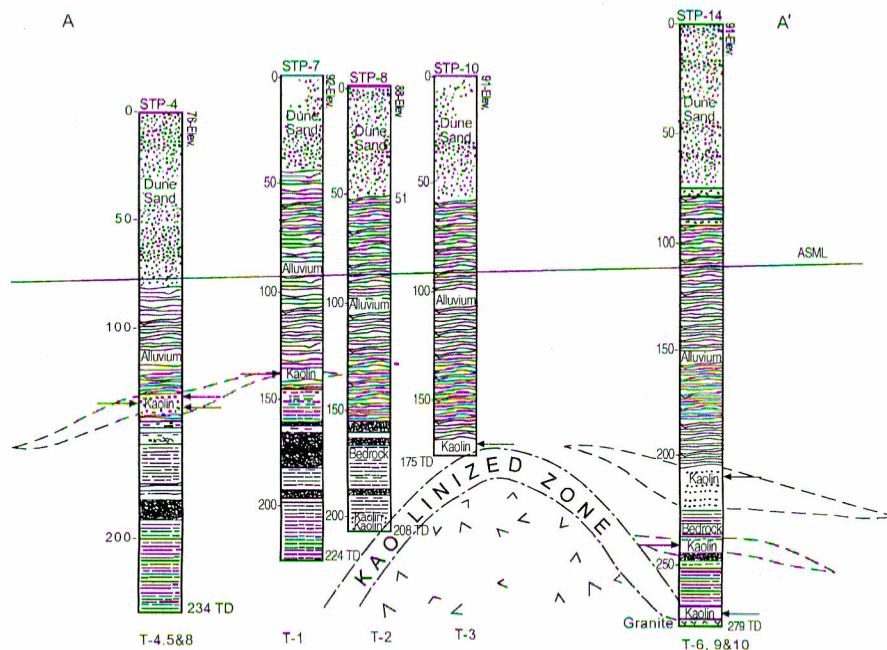

Fig. 2. Cross section correlation of kaolin in the drill holes of Thar coal basin, Sindh, along section lines AA′ and the depth of kaolin samples.

Samples of clay (< 2 µ) fraction grain size were procured and their slides were prepared by using the method described by Baig (1984). All slides of the clay fraction, were given the conventional treatments, described by Weaver (1989) and Grim (1968). Identification of the species of clay minerals, particularly the polytypes of kaolinite family, was made by scanning the oriented slides, following the X-ray diffraction technique, mentioned by Klug and Alexander (1974). The oriented and treated slides of clay (< 2 µ) fraction grain size and that of random powder samples were scanned on X-ray diffractometer from 2°, 2θ-40°, 2θ and 2°, 2θ-65°, 2θ.

Drying and crushing of samples. *Removal of moisture.* The selected core samples were left in an oven at 110 °C for over-night to remove the moisture. A representative portion of each dried sample was ground by hand in agate mortar and pestle for about 15 min. Mechanical grinding was avoided because it destroys the lattices of clay minerals (Baig, 1984). Powder thus obtained was used for the preparation of random powder samples and oriented slides. X-ray diffraction technique, described by Klug and Alexander (1974), was used in the present study for the analysis of minerals.

Removal of carbonate. Powdered samples were treated with 1M acetic acid solution for 24 h to remove carbonate (CaCO₃). After 24 h soaking in acid, the treated samples were subjected to three/four successive decantation and re-suspension in distilled water to remove carbonate and prevent flocculation.

Preparation of oriented slides. About 10 g powder of each sample was added to distilled water in a 250 ml beaker. Two or three grains of calgon (sodium hexa metaphosphate) were added to prevent the flocculation. The beaker was thoroughly shaken in an ultrasonic tank (50-100 watts) for about 35 min, for disaggregation of clay particles. Afterwards, the beaker was left untouched for four hours to allow the non-clay fraction of the suspension to settle down at the bottom of the beaker. The upper 4 cm suspension, which contained the clay (< 2 µ) fraction grain size sediment, was transferred to a test tube, which was centrifuged till the clear water appeared in the test tube. The settled fraction in the bottom of the test tube consisting of clay (< 2 µ) fraction grain size, was spread and smeared on to a glass slide with the help of a spatula. Four slides of the clay (< 2 µ) fraction of each sample were prepared and were given the conventional treatments i.e. glycolation, (G), heat treatment (H), and acid digestion (A/D). These treatments help in the identification of different species of clay minerals. Oriented slides of clay fraction were prepared according to the method stated by Baig (1997).

Normal slide. This is untreated slide of clay (< 2 µ) fraction, grain size, marked as N. This slide was run on the XRD from 2°, 2θ-40°, 2θ. This range of scan gives all peaks of the clay minerals, present in the sediments at their respective d-spacing.

Glycolated slide. This is the second slide marked as G. It was given the glycolation treatment by placing it in a desiccator containing glycol. The desiccator was placed in an oven at 60 °C for about an hour. This treatment is given to confirm the presence of mixed-layer clay minerals such as smectite, vermiculite etc. If these minerals are present, they show expansion in their d-spacing on glycolation for example, smectite expands from 16.5 A° to 13.3 A° and kaolinite shows slight decrease in its peak height (Srodon, 1980).

Heat-treated slide. This is the third slide marked as H. Heat treatment was given in an oven, set at 550 °C, for an hour. By this treatment structural change takes place in kaolinite and its basal reflections at 7.16 A°, 3.57 A° and 2.28 A° do not appear on X-ray diffraction. The 001 reflection of mineral chlorite shows enhancement at 14 A° peak and illite peak at 10 A° becomes more symmetrical, whereas the smectite peak collapses to 9.6 A° The heat treatment plays very important role in distinguishing the polytypes i.e. dickite, nacrite and halloysite of kaolinite family. At 550 °C the basal reflections of kaolinite disappeared, whereas the peaks of dickite were not affected. On further heating upto 650 °C, dickite peaks also disappeared, confirming its presence (Fig. 4a).

Acid digested slide. This is the fourth slide of clay (< 2 µ) fraction grain size, marked as A/D. The clay (< 2 µ) fraction grain size, was boiled in 1:1 HCl for about 15 min; after cooling, the slurry was smeared on a glass slide with the help of spatula. Kaolinite and chlorite, if both are present in the same sample, give XRD reflections at the same d-spacing. This treatment removes chlorite, if present in the sample, leaving kaolinite unaffected.

X-ray diffractometry. Klug and Alexander (1974) have mentioned that X-ray diffraction technique is the most accurate method for quick analysis of minerals in rocks, particularly the minerals present in the fine-grained sedimentary rocks and clays (< 2 µ) grain size. This technique was applied in the present investigation. A fully automatic X-ray diffractometer, Siemens D-5000, operating at 40 Kv and 20 mA, using Cu filter Cu Kα radiations, was used. The settings on the XRD were as under:

XRD settings	Random powder	Clay fraction
Scanning Range	2,° 2θ-65°, 2θ	2,° 2θ-40°, 2θ
Time constant	1 sec	4 sec
Step size	0.050 degree	0.050 degree
Step sampling	0.2 degree	0.2 degree

Mineral composition of random powder samples. The whole-rock samples, randomly loaded in a specially prepared powder holder, were scanned on the XRD from 2°, 2θ to 65°, and 2θ. Weaver (1989), Klug and Alexandar (1974), Grim (1968), and Schultz (1964), have mentioned that minerals, present in appreciable amounts in samples, show their presence by their specific d-spacing within the above mentioned range on X-ray diffraction. Minerals, present in the whole-rock samples, were identified on the basis of their d-spacing, mentioned by Weaver (1989), Chen (1977), Grim (1968) and Schultz (1964). Description of each mineral is given below:

Kaolinite. In the random powder samples kaolinite was identified by its diagnostic d-spacing at 7.16 A°, 3.57 A°, 2.49 A°, 2.34 A° and 4.36 A°, The sharp and very strong XRD peaks, shown by the kaolinite (Fig. 4a), indicated that it is well crystalline and also suggested its occurrence as a major constituent. The well crystalline nature of kaolinite suggested that its mode of formation is hydrothermal. Baqri (1978), observed an increase in the degree of crystallinity in kaolinite samples from the Nagarparkar area. He linked it with the leaching processes. The presence of detrital and authigenic kaolinite in the Tharparkar coal field is not unusual. Many workers including Baqri (1992, 1984 and 1978), Hughes (1971), Waage (1961), Glass (1958) and Grim and Allen (1938) have reported the presence of detrital and authigenic kaolinite in the coal basins in the world.

Quartz. Mineral quartz showed its presence in all the studied samples of the cores by its diagnostic d-spacing at 3.34 A°, 4.26 A°, and 1.817 A°, suggesting that it is a low temperature quartz (alpha quartz). Occurrence of alpha quartz has been reported as intergrowth with orthoclase/microcline in graphic granite. According to Kerr (1977), alpha quartz often occurs as the late interstitial mineral. Microscopic examination of the coarser fraction of the studied samples also indicated the presence of abundant grains of terrigenous quartz, which were moderate to well sorted, indicating that quartz grains have experienced many cycles of erosion and sedimentation and also have travelled over a long distance, before reaching the basin of the deposition.

Anatase. Anatase (TiO_2) is one of the rarest polymorphs of rutile (XO_2) group. Many petrologists have reported its occurrence in granite, granite-pegmatite, gneisses and mica schists. In the present study, the presence of anatase was detected in the random powder samples by its d-spacing at 3.51 A°, 1.98 A° and 2.38 A°. Anatase, both of authigenic and detrital origins, may be present in the studied samples. The igneous activity on Tharparkar granite, responsible for the kaolinization of feldspar by the action of interstitial solutions,

according to Pettijohn (1975), may be the process for the formation of authigenic anatase (TiO_2). Grim (1968) mentioned that anatase is a universal mineral compound of kaolinite. Titanium was probably available in sufficient amounts in the environments of deposition of the studied sediments. According to Krauskopf (1979), granite, basalt and crust of the earth contain 2,300 ppm, 9,000 ppm and 5,700 ppm of titanium, respectively. Dolcator *et al.* (1970), mentioned that upto 15% titanium is present in the structure of kaolinite. It is possible that sufficient amount of titanium, released from the Tharparkar granite and kaolinite, during the hydrothermal action, lead to the formation of authigenic anatase. Some amount of the detrital anatase, according to Berry and Brian (1959), might be contributed by the metamorphic and igneous rocks which are associated with the Nagarparkar granite.

Mineral composition of the clay fraction. Kaolinite, dickite and nacrite are three poly-types of kaolin group, identified in the clay fractions, as under:

Kaolinite. The scanning of normal slide (N) indicated the presence of kaolinite [$Al_2Si_2O_8(OH)_4$], by its diagnostic d-spacings at 7.16 A°, 3.57 A°, 2.49 A° and 2.338 A° (Fig. 4a). Kaolinite, chlorite and dickite give their basal reflections at the same d-spacings. Kaolinite is the main mineral of kaolin group. Its staking is of 1M type, it means "one layer" monoclinic. Kaolinite actually is 1Tc, due to triclinic system. Very little ionic substitution in minerals of kaolin group takes place. Small amount of Fe^{+3} and titanium is substituted for aluminum in kaolinite. Such substitution is restricted in poorly crystallized kaolinite. To confirm the presence/absence of these minerals, the other two prepared slides, marked as H and A/D, were scanned on the X-ray diffractometer. The slide H, which was given the heat treatment at 550 °C, did not show any reflection for kaolinite (Fig. 4a), because at this temperature due to dehydroxylation, the structure of kaolinite is destroyed and the basal reflections are lost, which is a typical behavior of kaolinite. For confirming the presence or absence of chlorite, the second slide marked A/D was scanned on the XRD. The acid digestion treatment completely removed chlorite from the sample, leaving the kaolinite unaffected. Thus, the d-spacings of A/D slide confirmed that there is no chlorite and only kaolinite is present in the sample.

Glass (1958) found more kaolinite in sandstone of non-marine origin than in the shales of marine origin. He attributed this kaolinite to the post-depositional mode of formation, suggesting its authigenic origin. Fuchtbauer and Goldschmidt (1963) also stated that disordered kaolinite, present in shale, changes into well crystallized form in sandstone. Prado (1963) mentioned that some clay minerals are developed by *in situ* alteration of feldspar to kaolinite.

Dickite. It is one of the polytypes of kaolin group minerals. Its structure is identical to kaolinite, except that empty octahedral site alternates between sites from layer to layer. Two layers are necessary to define its unit cell and this polytype is 2M, i.e. two layer monoclinic. It is very difficult to distinguish between the kaolin polytypes. Dickite and nacrite both have identical theoretical composition and their layers are stacked in alternating regular sequence (Weaver, 1989). Mineral dickite has a 2-1 layered monoclinic cell (Newnham and Brindley, 1956), whereas nacrite is a 6-layered monoclinic cell (Hendricks, 1938). It is the rarest mineral of kaolin group which is produced probably by the activity of hydrothermal solutions on kaolinite. Usually it occurs quite commonly as secondary clay in the pores of sandstone. Weaver (1989) mentioned the occurrence of dickite in coal beds also. He stated that dickite can be considered as a regular alteration of right and left handed kaolinite layers. Shutov *et al.* (1970) mentioned that during the burial of sediments, gradual transformation of kaolinite to dickite is very common. According to them, during the deep burial of sediments, veins of dickite are formed which under the strong stress condition are converted into nacrite.

Dunoyer-de-Segonzac (1970), reported the presence of dickite in the sandstone of cretaceous age in Cameroon. According to him, this dickite was formed at the temperature range of 70-90 °C. This example shows that the temperature may vary for the formation of dickite and its formation depends not only on the temperature, but also on the physicochemical conditions of the environments which play an important role. For the identification of dickite, the oriented slide was heated upto 550-600 °C. Dickite and kaolinite both gave reflections at the same d-spacing i.e. 7.16 A°, 3.57 A°, 2.49 A° and 2.338 A°. The heat treatment, given to the oriented slide at 550 °C, destroyed only the basal reflections for kaolinite due to dehydroxylation. The XRD reflections which were retained at this temperature and existed upto a temperature of 600 °C and lost at 650 °C due to dehydroxylation, confirmed the presence of dickite in the slides T-7, T-10, (Fig. 4a).

Nacrite. This is the rarest polytype of kaolin family. Brindley and Brown (1980) presented X-ray data for the identification of the kaolin polytypes. The structure of nacrite is similar to other polytypes. It is made up of unit layer of an alumina octahedral sheet and a silica tetrahedral sheet like kaolinite. It differs in stacking and in the arrangement of aluminum ions in octahedral position. The unit cell of nacrite is made up of six unit layers, each having the arrangement described for kaolinite. Nacrite dehydroxylates at 680-700 °C.

Quartz. Mineral quartz, indicated its presence in the clay ($< 2\ \mu$) fraction grain size on X-ray diffraction, by weak and diffused reflections at the d-spacing 3.34 A° 4.26 A° and

1.817 A°. The weak reflections (Fig. 4a) indicated small amount of quartz in the clay ($< 2\ \mu$) fraction grain size.

Results and Discussion

The scanning of the random powder and the slides of clay ($< 2\ \mu$) fraction grain size, revealed that kaolinite occurs as the dominant mineral, in both the fractions of samples as illustrated by Fig. 3, 4a and 4b. Anatase and quartz, in random powder and dickite in clay ($< 2\ \mu$) fraction grain size, showed the presence of their subordinate amounts. X-ray diffraction of the random powder and that of clay ($< 2\ \mu$) fraction grain size samples indicated that kaolinite, quartz and anatase are the main constituents of the whole-rock and the clay ($< 2\ \mu$) fraction grain size is composed of kaolinite, dickite and quartz.
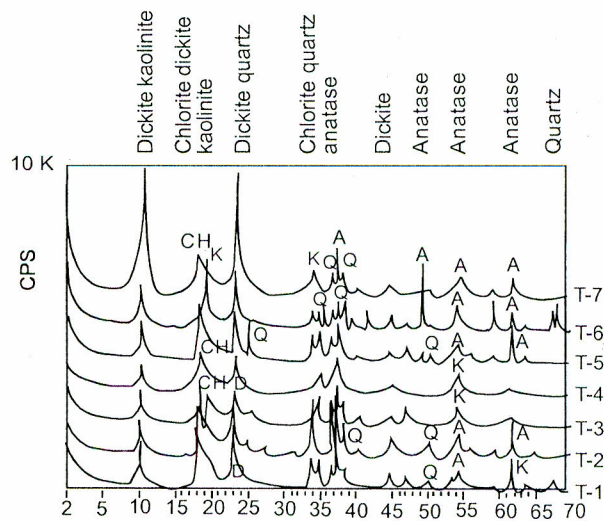

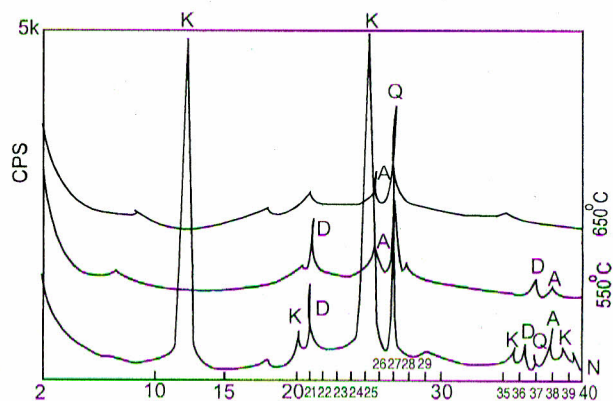**Fig. 3.** XRD trace of random powder samples.

Fig. 4a. XRD trace of normal and heat treated slides of clay fraction samples.

Kaolinite. XRD trace of random powder samples, shown in Fig. 3, indicated that kaolinite occurred as the main mineral, whereas both anatase and quartz were present in the subordinate amounts (Table 2). The diagnostic d-spacing, used for the identification of non-clay and clay minerals are shown in Fig. 3 and are mentioned in Table 3.
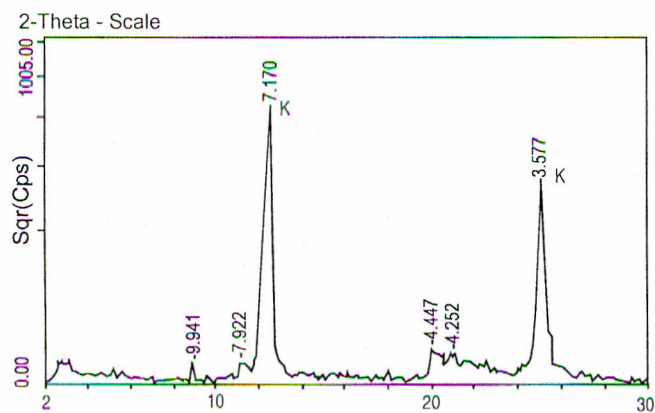

Fig. 4b. XRD trace of the glycolated slides of clay fraction samples.

Table 2. Minerals in samples

Minerals in whole rock samples (in order of abundance)	Minerals in the clay (< 2 μ) fraction grain size (in order of abundance)
Kaolinite	Kaolinite
Quartz	Dickite
Anatase	Quartz

Minerals identified in the studied samples are mentioned in Table 2. Kaolinite is present as the major component in both the fractions of the studied samples. It showed its strong and sharp reflections on X-ray diffraction; some samples also showed poor and diffused peaks for kaolinite. The sharp, strong and diffused reflections indicated the presence of well crystalline and degraded types of kaolinite. The kaolinite which gave sharp reflections may be of authigenic origin. This mode of formation of kaolinite in the studied sediments is possible, because the Nagarparkar granite complex contains abundant amount of feldspar. Formation of authigenic kaolinite, by the hydrothermal alteration of feldspar, is a well-known process. Shutov et al. (1970) mentioned that the authigenic kaolinite may also be produced by the metagenesis of feldspar.

The kaolin present in samples T-1, T-4, and T-5, in the bore holes STP-4 and STP-7, is underlain by the alluvium, indicating its recycled nature, whereas the kaolin in samples T-2, T-3 and T-6 showed that it is resting on the Nagarparkar granite complex in the bore holes, indicating its authigenic origin (Fig. 2). Kaolin, present in STP-14 bore hole, illustrates its association with the sediments and also with the Nagarparkar granite. This association suggested that the authigenic kaolinite were produced as a result of kaolinization, (Shutov et al., 1970). The position of the bore holes STP-8, STP-10 and STP-14 drilled on the granite basement and that of STP-4 and STP-7 drilled away from the granite mass is illustrated in Fig. 2. The observed association of kaolinite in the bore holes strongly supports the idea of authigenic as well as of detrital origins of the kaolinite.

The authigenic origin of kaolinite, in these sediments can also be explained by taking into consideration the phenomenon of creation of the acidic environments, which were produced

Table 3. Diagnostic d-spacing used for the mineral identification

Quartz	I (%)	Anatase	I (%)	Kaolinite	I (%)	Dickite	I (%)
3.343 A° 26.68, °2è	100	3.52 A° 25.30, °è	100	7.14 A° 12.39, °2è	10+	7.16 A° 12.36, °2è	10+
4.26 A° 20.85, °2è	35	2.43 A° 37.79, °è	33	3.58 A° 24.87, °2è	10+	3.58 A° 24.87, °2è	10+
2.28 A° 39.52, °2è	17	2.38 A° 38.48, °è	22	2.49 A° 36.06, °2è	08	4.27 A° 20.80, °2è	09
1.817 A° 39.52, °2è	12	2.34 A° 48.08, °2è	--	2.34 A° 38.48, °2è	09	2.51 A° 35.77, °2è	06
–	–	–	–	–	–	2.23 A° 38.81, °2è	05

during the sedimentation, due to the release of CO_2 in the early stage of coalification. Authigenic kaolinite is formed, when the primary silicates of alumina are subjected to chemical weathering at pH 5 to 7 in oxidizing environments. The necessary conditions, required for the formation of authigenic kaolinite, as explained earlier, were present in the Tharparkar coal basin.

The sharp, poor and diffused XRD reflections, shown by the kaolinite, suggested that in some samples degraded/detrital kaolinite is present. Degraded kaolinite, might have suffered many cycles of erosion and sedimentation, before reaching the Tharparkar coal basin. The explanation given above, justifies the authigenic as well as the detrital modes of formation of the kaolinite, present in the studied sediments.

Dickite. It is the second clay mineral, encountered in the present study. It is one of the members of kaolin family. Dickite commonly occurs in the form of pellets as pore fillings in sandstone. It resembles kaolinite and its plates usually are well developed with a hexagonal shape which can be seen only with a scanning microscope (SEM). Unfortunately, in the present investigation, this study could not be under taken. Dickite is the alteration product of kaolinite. It is usually produced by the gradual transformation of kaolinite. Shutov *et al.* (1970) reported that kaolinite gradually transforms into dickite during the burial of sediments. According to him, during the deep burial of sediments, veins of dickite are produced, and these veins, under the influence of strong pressure conditions, prevailing in the basin of deposition, are converted into nacrite, a very rare polytype of the kaolin family. The complete absence of nacrite in the studied samples, suggested that the physicochemical conditions including the type of pressure, required for the alteration of dickite into nacrite (Shutov *et al.*, 1970) were not prevalent in the Tharparkar coal basin during the process of the coalification.

Weaver (1989), stated that dickite may be produced as a result of regular alteration of the right and left handed kaolinite layers. Many clay mineralogists believe that a higher temperature is required for the formation of dickite, as compared to kaolinite. But Dunoyer-de-Segonzac (1970) stated that a higher temperature is not always required for the formation of dickite. He referred the presence of dickite in the cretaceous sandstone of Cameroon. According to him this dickite was produced in the temperature range of 70 to 90 °C. It shows that for the formation of dickite, a high temperature condition is not required. The physicochemical conditions, existing in the depositional basin, may also play an important role for the formation of authigenic dickite in sediments.

Dunoyer-de-Segonzac, (1970), further stated that in deep diagenesis, the crystallographic evolution of kaolin minerals may take place in the order of kaolinite-kaolinite/dickite - dickite - nacrite/nacrite.

Anatase. Anatase (TiO_2) is the third mineral, present in the investigated samples. Attempt has been made to explain its origin and provenance. Hurlbut and Klein (1977) mentioned that anatase is one of the rarest polymorphs of rutile (XO_2) group. It occurs in granite, granite-pegmatite, gneisses and mica schists. Berry and Brian (1959), also mentioned that authigenic anatase, may be produced by the leaching effect of hydrothermal solutions on the gneisses and schists. Anatase usually results from the alteration of other titanium bearing minerals. Rutley (1988) stated that the formation of anatase usually takes place by the alteration of other titanium bearing minerals. According to Brindley and Robinson (1947), anatase is produced in the last stage of the decomposition of titaniferous iron oxide components present in the sediments. They also reported presence of anatase in the coal measures of the Yorkshire, and also in the fire clay deposits of Ayrshire Central Scotland. It appears that anatase of both origins, i.e., detrital/allogenic and authigenic, is present in the studied sediments. Anatase of detrital origin might have been contributed by the weathering product, released from the Nagarparkar granite and its associated metamorphic rocks. Dolcator *et al.* (1970) mentioned that 15% titanium is present in the structure of kaolinite. Krauskopf (1979), stated that granite contains 2,300 ppm of titanium. Sarkisyan (1972), pointed out that the degeneration and regeneration of kaolinite, during the kaolinization process, contribute sufficient amount of titanium to the depositional environments for the formation of authigenic anatase. The effect of hydrothermal activity on the Nagarparkar granite and its associated metamorphic rocks and the leaching of the kaolinite, in the Tharparkar coal basin, might have released sufficient amount of titanium, for the formation of anatase. Some amount of detrital anatase, present in the studied samples, is contributed by the weathering of igneous and metamorphic rocks, associated with the Nagarparkar granite, as suggested by Berry and Brian (1959). The presence of minerals of detrital origin i.e. quartz, kaolinite and anatase etc. along with some iron oxide in the studied sediments, all suggested a near-shore deposition for these sediments, under the reducing and micro-oxidizing environments. The presence of detrital kaolinite in sediments has been considered an important indicator of the proximity of shoreline and paleo-geography of the area.

Conclusion

The following inference may be made from the above study:

• Kaolinite, both of authigenic and detrital origins, is present as the main constituent in the clay fraction and random

powder samples. Kaolinite of detrital origin, present in some samples, might have arrived in the basin of deposition from the distant areas, where the weathering was in progress.

• Dickite of authigenic origin is also present in the clay ($< 2\,\mu$) fraction grain size samples. It was produced by the weathering or the decomposition of kaolinite, due to the increase in temperature, as a result of the intrusion of granitic mass in the Tharparkar area.

• Alpha quartz is present in samples of the whole-rock as well as in the clay ($< 2\,\mu$) fraction grain size. It has been contributed by the weathering of the pre-existing igneous complexes.

• Anatase (TiO_2) of authigenic and detrital origins is present in the studied sediments.

• Presence of detrital minerals i.e. kaolinite, quartz and anatase and iron oxide in the studied sediments, all strongly suggest that these sediments were deposited near-shore, under the shallow marine and micro-oxidizing environments.

• Presence of kaolinite in sediments has been considered the indicator of the proximity of shoreline and paleogeography of the area. In the studied sediments, kaolinite occurs as the major detrital component, strongly supporting the idea of the near-shore deposition of the sediments of Tharparkar coal basin.

Acknowledgement

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