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Reservoir characterization and rock eval pyrolysis of clastic sedimentary rocks in the Geku Formation, Arunachal Pradesh, North-eastern India

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ABSTRACT

The present investigation aims to decipher the reservoir quality and source rock potential of the sandstones and shales of the Geku Formation of the Yinkiong Group, Eastern Himalaya, NE India. To achieve the goal, sandstone petrography and rock-eval pyrolysis of shale aided with X-Ray diffraction have been employed. A petrographic study revealed that the detrital constituent of the sandstones is mainly quartz, feldspar, and lithic fragments. Authigenic cements such as carbonate and clay bind the detrital materials as indicated by petrographic as well as X-Ray diffraction study. Clay minerals include illite, smectite-montmorillonite and kaolinite. The studied sandstones underwent compaction as evidenced by the formation of concavo-convex and sutured grain contacts, which also suggest its phyllomorphic stage of diagenesis. The presence of calcite and clay cement has led to reduction of the porosity and permeability of sandstones, which is also substantiated by sorting and irregular grain shapes such as sub-angular, angular, and sub-rounded, thereby affecting reservoir quality. The rock eval pyrolysis data suggests that the Yinkiong shales have poor source rock potential with dominantly kerogen type III. The geochemical parameters of the studied shales suggest mostly immature and postmature organic matter and the very low TOC values indicate poor organic richness.

Keywords: Geku Formation, Petrography, Reservoir characterisation, Diagenesis, Rock eval pyrolysis

INTRODUCTION

Rift basins are known to bear abundant hydrocarbon reservoirs and source rocks worldwide (Morley, 1999). But structural deformations and basin fill stratigraphy also comes into play while determining whether it has hydrocarbon bearing potential or not (Lambiase and Morley, 1999). The stratigraphic succession in the syn- and post-rift phases of basin evolution is largely responsible for the presence and distribution of hydrocarbons in rift basins. The kind of post-rift tectonics and whether marine or non-marine strata predominate in basin fill are important factors (Lambiase and Morley, 1999).

The Paleogene sediments of Eastern Himalaya have been deposited in a rift basin, which developed after the north-eastern edge of the Indian plate separated and begun to rotate clockwise during India-Asia collision (Beaumont et al., 2001; Cook and Royden, 2008; Houseman and England., 1993; Sarma et al., 2020). The Himalayan orogenic movement began as a result of north-south compressional forces caused by the India-Asia collision. As the Burmese Plate continued to converge further, which deformed the rift basin sediments (Sarma et al., 2020). After the development of the rift basin, the Yinkiong Group rocks were thrusted and hence intensely deformed due to a WNW-ESE compressional force which was created when the Indian plate started colliding with the Burmese plate (Sarma et al., 2020). Moreover, the Geku Formation sediments have been found to be of continental facies which deposited in a terrestrial environment, although there was a shift in provenance and the depositional environment in the foreland basin changed to marine which could be the

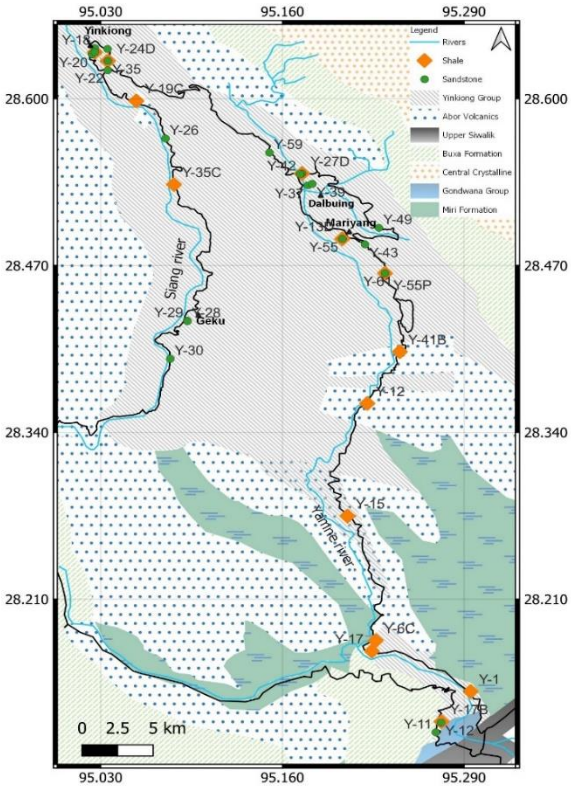


Fig. 1: Geological map of study area (Modified after Acharyya, 2007; Taye, 2015; Taye & Bhattacharyya, 2017)

result of the collision between the Indian and Asian plates (Baral et al., 2019; Bordoloi et al., 2022). One significant factor that contribute to rift-basin stratigraphy, and hence, hydrocarbon potential, are whether the syn- and post-rift basin fill is dominantly marine or non-marine sediment. It has been found that rifts with marine fills are more prolific hydrocarbon reserves than those with non-marine rifts (Lambiase and Morley, 1999).

Tripathi and Mamgain (1986) compared the larger foraminiferal assemblage record from Subathu Formation with that from Yinkiong Group of Eastern Himalaya in similar stratigraphic/tectonic setup and suggested the continuity of Subathu sea all along the Himalayan frontal zone up to Arunachal Pradesh (Tripathi et al. 1981; Tripathi and Mamgain, 1986; Chutia et al. 2019; Jafar and Singh, 1992). Similar Palaeocene to Miocene marine strata has been reported from Gamba, Tingri and Yadong sections in southern Tibet and throughout the Himalaya and were correlated with the Yinkiong and Subathu Formation (Jiang et al., 2016). Organic geochemical analysis of Subathu Formation has suggested the prevalence of Type III (gas prone) kerogen with high TOC content (average 7.5%). These rocks have been found to exhibit poor to excellent hydrocarbon potential with Tmax and Ro (vitrinite reflectance) values indicating wet gas to dry gas generation window (Hafiz et al., 2022). Hydrocarbon potential study of Subathu Formation sediments based on palynofacies analysis and Thermal Alteration Index values has indicated that these sediments display moderate to good gaseous hydrocarbon generation (Thakur and Dogra, 2011).

In Holocene stratigraphic division, the prospect of sedimentary environment and coal accumulations has been accomplished by a few scholars but there hasn't been a significant development in Palaeocene-Eocene oil and gas exploration. The Yinkiong Group of the Eastern Himalayas, due to its unique stratigraphic position, has been a topic of discussion lately. Few scholars (Tripathi et al., 1979; Singh.,1984; Chutia et al., 2019; Baral et al., 2019; Sarma et al., 2020; Bordoloi et al., 2022) have extensively studied the eastern Himalayan Cenozoic sediments with the help of geochemistry, petrography, clay mineralogy and tectonics to evaluate the depositional environments. But no detailed reports on hydrocarbon potential of the Yinkiong Group in terms of reservoir quality and source rock potential have been found. Hence, the proposed study is encouraged by the lack of hydrocarbon potential study of sediments in the Eastern Himalaya (Fig-1). The present study encompasses the characterization of reservoir and source rock potential of sandstones and shales based on petrography, X-Ray diffraction, and rock eval pyrolysis data.

REGIONAL GEOLOGY AND TECTONICS

The Geku formation of Yinkiong Group comprises sedimentary rocks consisting of variegated shale (grey, green and purple) with sandstone of Palaeocene-Eocene age and are exposed along the Siang and Yamne river sections. The rocks of these areas are intensely deformed with complex folding and varies in age from Late Palaeocene to early Eocene. These Paleogene rocks have been believed to hold the record of events that occurred during India-Asia collision. The Main Central Thrust (MCT) and the Main Boundary Fault (MBT) are two major tectonic features of Eastern Himalayas as it is in the western Himalayas. The MBT marks the boundary between the Palaeocene-Eocene Yinkiong Group and the Siwalik Group, where the Siwalik sediments have been thrusted over by the older sediments in the Siang valley and is of ENE-WSW trend (Kumar, 1997). These rocks have undergone intense deformation and have been faulted and folded into anticlines and synclines with axial planes dipping towards north west of the Siang valley. The Himalayan orogeny had quite a significant influence on the sedimentation of Siang valley. The India-Asia collision took place during the Palaeocene-Eocene at ~65 Ma resulting in the separation of the north-eastern edge of the Indian plate and this portion underwent a clockwise tectonic rotation due to compression and commenced the development of a rift basin, where Yinkiong Group sediments were deposited during Late Palaeocene-Early Eocene (Beaumont et al., 2001; Cook and Royden, 2008; Houseman and England, 1993; Sarma et al., 2020). The India-Asia collision gave rise to N-S compressional forces and this marked the beginning of Himalayan orogeny (Sarma et al., 2020). Later, the Indian plate converged with the Burmese plate to produce WSW-ENE compressional forces and due to these two compressions, thrusting took place over Palaeocene-Eocene sediments and gave rise to a number of faults and tight folds and deformation of Yinkiong Group sediments took place (Sarma et al., 2020). At the centre of the Siang Window in the Eastern Himalayan Syntaxis, a deep sequence of fossiliferous Paleogene sediments interbedded with the Abor Volcanics is exposed beneath up-arched MBT (Acharyya, 1994; Sengupta et al., 1996). Although these sediments tectonically hidden in the foothills of Bhutan and Arunachal Pradesh, the Palaeogene sediments are well exposed at the centre of the Siang Window at the Eastern Himalayan Syntaxis. (Acharyya, 2007). In the upper and east Siang districts of Arunachal Pradesh, there is a laterally continuous exposure of Yinkiong Group of rocks along Mariyang-Yinkiong and Yinkiong-Geku road sections (Chutia et al., 2019; Bordoloi et al., 2022). The Yinkiong Group is divided into the late Palaeocene to early Eocene lower Geku Formation consisting of fine-medium grained sandstone and variegated shale (purple, grey, and green) associated with basic volcanics and early to middle upper

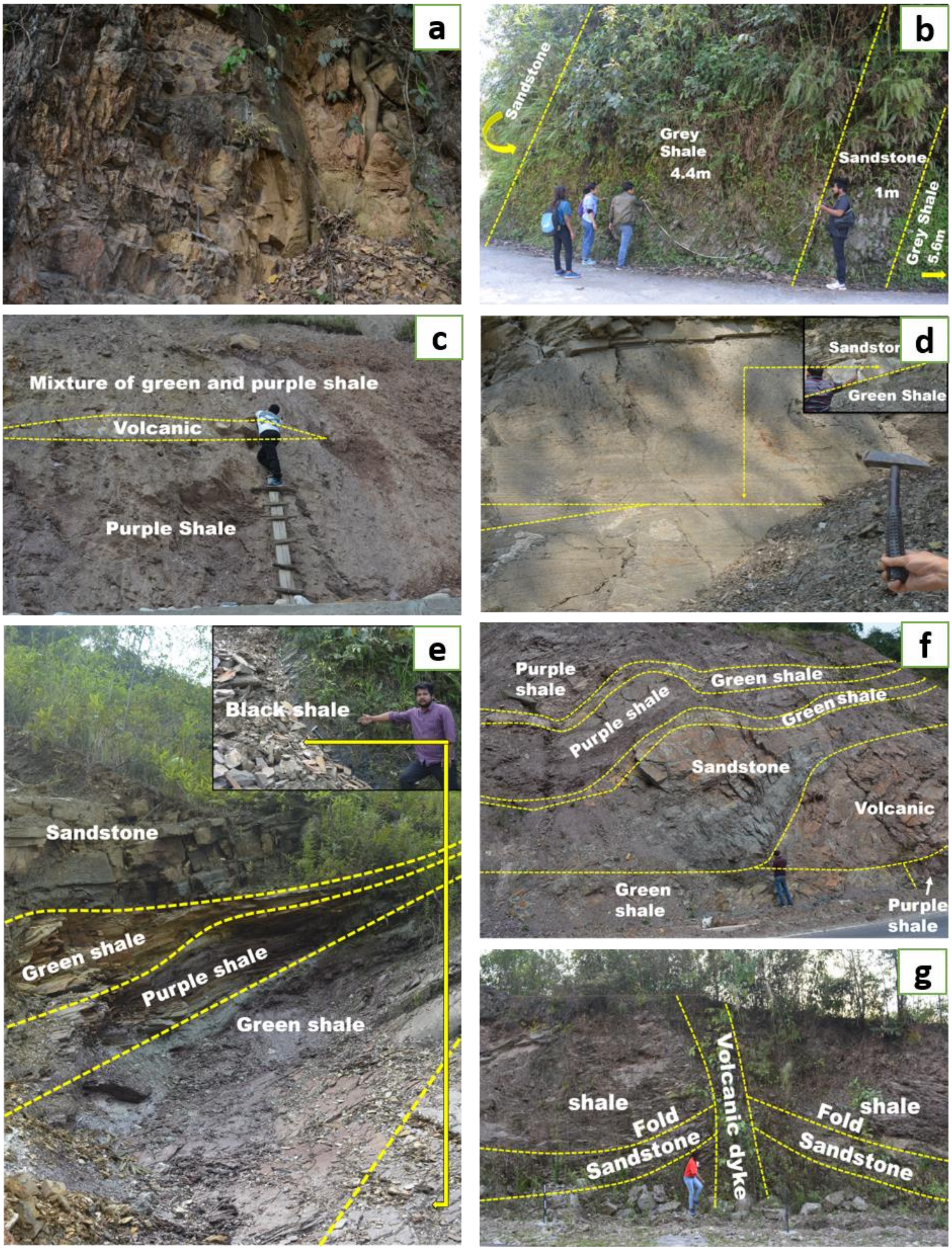


Fig. 2: (a) Well bedded sandstone Geku type section sandstone, (b) An outcrop of shale-sandstone alteration; The sandstone exposed here is fine to medium-grained exhibiting thin laminae, (c) An outcrop of purple and green shale with a band of intermixed volcanics in between the shale beds, (d) Sandstone and shale exposures with sandstone exhibiting ripple marks and current beddings, (e) An exposure of Sandstone-green shale-purple shale-green shale-black shale alteration, (f) Large exposure of green shale-purple shale-sandstone alternations with volcanic below and above green shale, and (g) A folded sandstone-shale outcrop intruded by volcanic dyke.

Eocene Dalbuing Formation comprising of shale, sandstone and limestone. The Geku Formation comprises of massive well jointed sandstones which are well exposed in and around Geku Town (Fig. 2a). The outcrop along Yinkiong-Geku road section, laterally along the left bank of Siang river with frequent sandstone-shale alterations (Fig. 2b) indicating a transitional environment of deposition. The concordant relationship between the volcanics and the folded and thrusted Yinkiong Group of rocks further points to syn-sedimentary volcanism in the shale-sandstone sequence (Fig. 2c). Cross bedded white to pale sandstones also exhibiting ripple marks are present near Mariyang on the way out of Dalbuing village (Fig. 2d). The Gondwana Group comprising of quartzite, sandstone and grey to black shale is thrusted over by the Yinkiong Group rocks and this contact is evident from the carbonaceous black shale in contact with the variegated shales of Geku Formation (Fig. 2e). The Abor volcanic rocks also show discordant relationship with Geku Formation in the form of dyke cutting across a sandstone and shale outcrop near Mariyang (Fig. 2f & 2g).

MATERIALS AND METHODS

Fresh samples belong to Yinkiong Group were collected along the Mariyang-Yinkiong and Yinkiong-Geku road section for a consolidated petrographic and rock eval pyrolysis study. Twenty-two fresh sandstone samples have been selected for petrographic investigation and studied under optical microscope at Department of Geology, Cotton University in order to examine the reservoir characteristics. During this procedure, detrital and diagenetic minerals and properties such as porosity and sorting were determined.

In order to detect the source rock potential of Yinkiong Group, a total of 15 shale samples were selected in order to obtain the pyrolysis data from which the kerogen type and maturity were determined. The samples were powdered and the pyrolysis was carried out as described by Hunt (1995) nd Lafargue et al. (1998). The geochemical data obtained from this analysis is then plotted to determine the maturation level and quality of kerogen. To determine TOC and Tmax, selected shale samples were examined using a Rock-Eval 6 instrument using the Basic/Bulk-Rock programmed pyrolysis procedure for source rocks at Indian Institute of Technology, Bombay (IIT). The clay mineralogical composition (including non-clay minerals) has been studied using X-Ray Diffraction (XRD) analysis. Pulverised fine bulk powder samples were considered for the XRD analysis, which was performed using Philips X'Pert Pro, a fully automated computerized powdered XRD technology (using Cu Kα radiations) at the Department of Instrumentation and USIC, Gauhati University and obtained X-Ray diffractogram patterns have been identified by following the published data (Tucker, 1988).

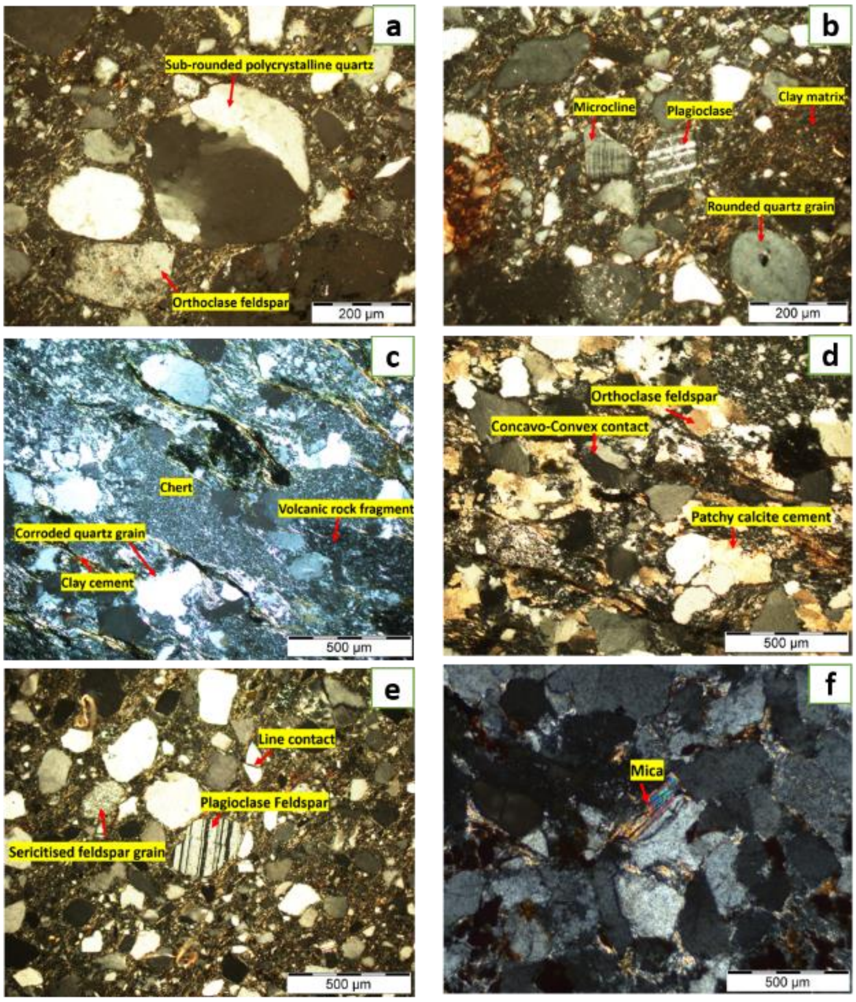


Fig. 3: Photomicrographs of sandstones showing: (a) Sub-rounded polycrystalline quartz and orthoclase feldspar in poorly sorted framework, (b) Microcline, plagioclase feldspar and a rounded monocrystalline quartz grain, (c) Intense deformation characterized by corroded quartz grain and stretched alignment of cement and grains, (d) Intergranular spaces occupied by calcite cement blocking almost all porosity, (e) Sericitized feldspar and another feldspar grain with prominent twinning; also displaying line contact owing to compaction, and (f) Bending of mica flakes, angular quartz grains and clay cement dominating a moderately sorted sandstone.

RESULTS

PETROGRAPHY

The petrographic study of sandstones reveals that they are fine to medium-grained comprising mostly of sub-angular to angular and sub-

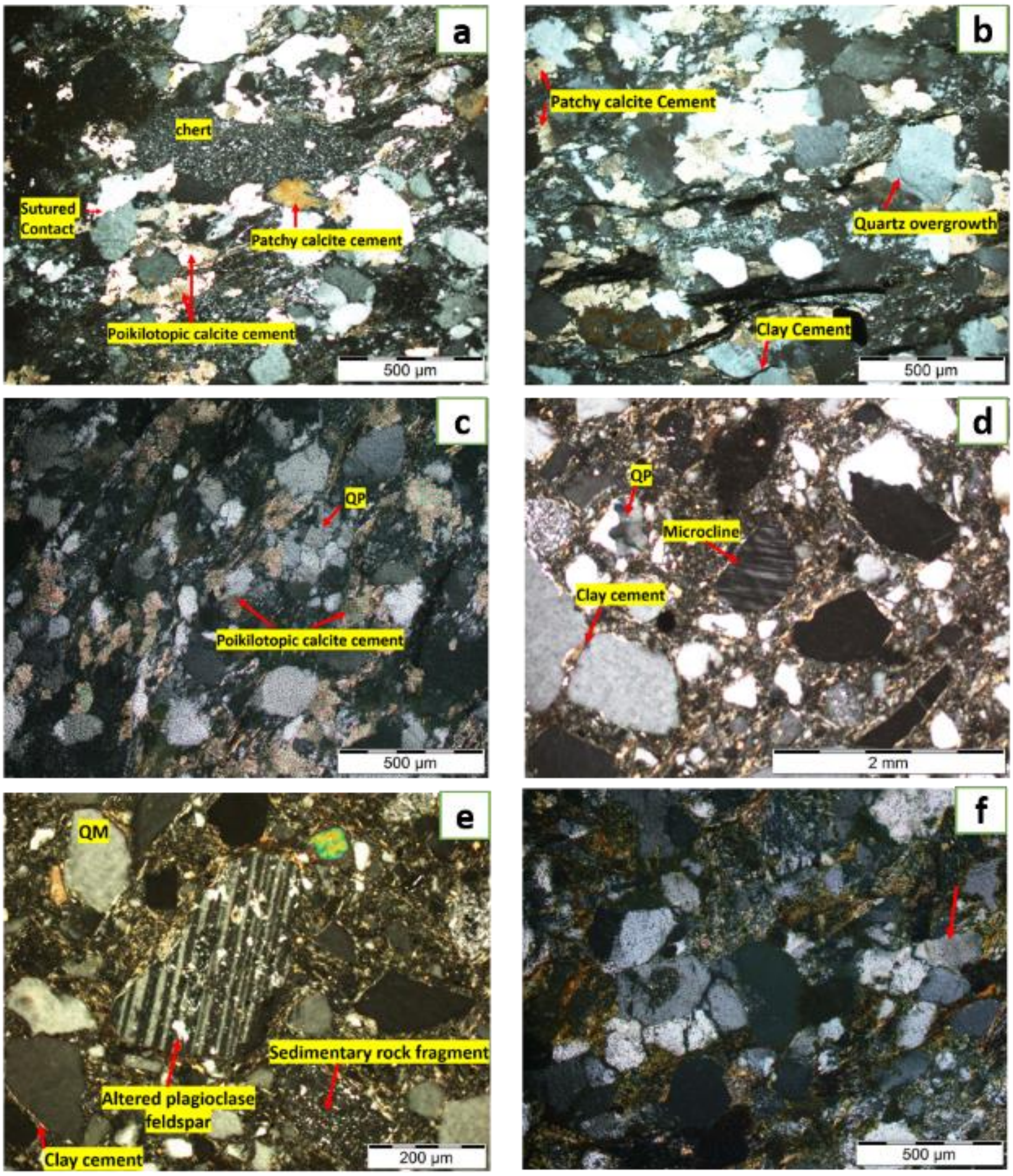


Fig. 4: Photomicrographs of sandstones of Geku Formation. (a) Typical calcite cemented sandstone with sutured grain contacts all indicating signs of compaction and cementation, (b) Patchy calcite cement and quartz overgrowth, (c) Poikilotopic calcite cement engulfing several quartz grains at a time. Also showing polycrystalline quartz (Qp) and quartz overgrowth, (d) Polycrystalline quartz and microcline, (e) Partially altered plagioclase feldspar, grain coating clay cement and sedimentary rock fragment in a poorly sorted sandstone, and (f) Partially albitized K-feldspar grains.

rounded quartz grains (Fig. 3a). Few rounded grains are also observed which are quartz and feldspar (Fig. 3b). All the sandstone samples are moderate to poorly sorted. Quartz grains present are both monocrystalline and polycrystalline, with an average quartz percentage 70 %. Some quartz grains have a relatively dense contact relationship such as line, concavo convex and sutured, because of which pores are significantly less (3d, 3e and 4a). Most of the quartz crystals are deformed and a few have undergone corrosion (Fig. 3c). The feldspar content in these sandstones is low and averages about 11.5%. Commonly found feldspar are orthoclase, microcline and plagioclase (Fig. 3d and 3e). The different feldspar grains vary in size from fine to coarse with subhedral shape. A few feldspars have also been sericitized (Fig. 3e). The mica grains present are bended (Fig. 3f) and platy and a few have been deformed when sandwiched between quartz grains and cement. Minor amounts of lithic fragments are also present. The main diagenetic elements found in the studied sandstones are cementation, compaction, alteration and development of different grain contacts. Cement types identified are mainly calcite, clay and silica (in the form of quartz overgrowths). Calcite occurs as patches as well as poikilotopic pore filling cement (Fig. 4a, 4b, and 4c). The mechanical compaction as a result of increased burial during diagenesis indicated by development of authigenic

TABLE 1: Results of rock eval pyrolysis of studied shales of Geku Formation

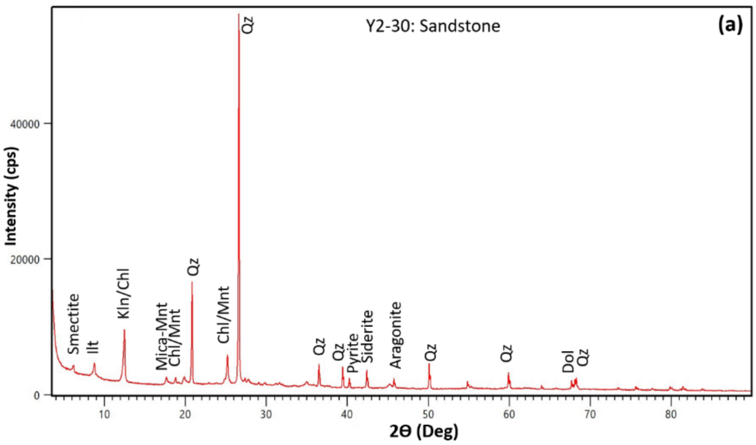
Sample no.	**Qty - (mg)**	**S1 (mg/g)**	**S2 (mg/g)**	**S3 (mg/g)**	**S1+S2 (GP)**	**S1/S1+S2 (PI)**	Tmax (˚C)	**HI**	**OI**	**TOC (%)**
Y2-17B	60.75	0.01	0.01	0.27	0.02	0.5	488	100	2700	0.01
Y2-41B	60.23	0.01	0	0.14	0.01	1	581	0	1400	0.01
Y2-61B	60.76	0.01	0	0.14	0.01	1	283	0	1400	0.01
Y2-19C	60.92	0.01	0	0.11	0.01	1	301	0	1100	0.01
Y2-35C	60.46	0.02	0	0.07	0.02	1	326	0	24	0.29
Y2-24D	60.86	0.01	0	0.08	0.01	1	499	0	0	0
Y2-27D	60.33	0.02	0.03	0.18	0.05	0.4	356	150	900	0.02
Y2-13D	60.67	0.02	0	0.06	0.02	1	549	0	300	0.02
Y2-27M	60.68	0.04	0.01	0.15	0.05	0.8	327	100	1500	0.01
Y2-55P	60.31	0.01	0	0.04	0.01	1	440	0	0	0
Y-1	60.56	0.02	0.12	0.1	0.14	0.13	433	133	111	0.09
Y-6C	60.61	0.01	0.05	0.11	0.06	0.2	449	83	183	0.06
Y-12	60.36	0.01	0.05	0.03	0.06	0.17	595	15	9	0.34
Y-15	60.71	0.01	0.03	0.19	0.04	0.19	450	7	41	0.46
Y-17	60.75	0.02	0.04	0.02	0.06	0.36	486	200	100	0.02
Average	60.59	0.015	0.023	0.11	0.038	0.65	437.53	52.53	651.2	0.09

quartz in the form of quartz overgrowths (Fig. 4c) and bending of mica flakes have greatly affected the reservoir quality of the studied sandstones. Calcite cement is fairly abundant in the sandstones blocking almost all of the porosity thereby controlling reservoir quality.

ROCK EVAL PYROLYSIS

The rock eval pyrolysis data are reported in Table 1. Tmax average value is about 437.5, which ranging from 283 to 595°C. The results show very erratic Tmax and PI (Production Index) values and low pyrolysis values such as S2 about 0.023 mg HC/g rock, S3 about 0.11 mg HC/g rock,

TOC about 0.09 wt. %, HI about 52.5 mg HC/g TOC and highly variable OI about 0-2700 mgHC/gTOC. Total organic carbon (TOC) content of the shale samples ranges from 0 to 0.46 and averages 0.09 %. Maximum TOC value is 0.46, which suggest poor organic richness. The studied samples show poor hydrocarbon generation potential, GP (S1+S2) with values ranging from 0.01 to 0.14 mg HC/g rock. The Production Index (PI) is an indication of the amount of hydrocarbon, which has been produced geologically relative to the total amount of hydrocarbon, the sample can produce. The PI (=S1/(S2+S3)) (Peters and Cassa, 1994) value of the studied shales, which is also an indication of thermal maturity, range from 0.13 to 1.0, which indicates immature to mature



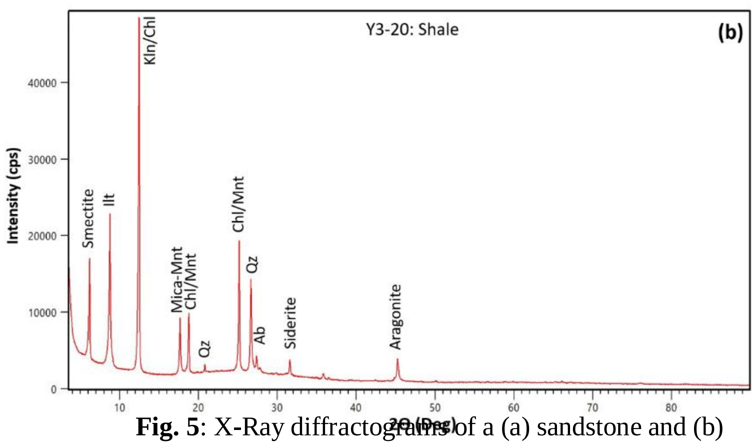


Fig. 5: X-Ray diffractograms of a (a) sandstone and (b) shale of the Geku Formation

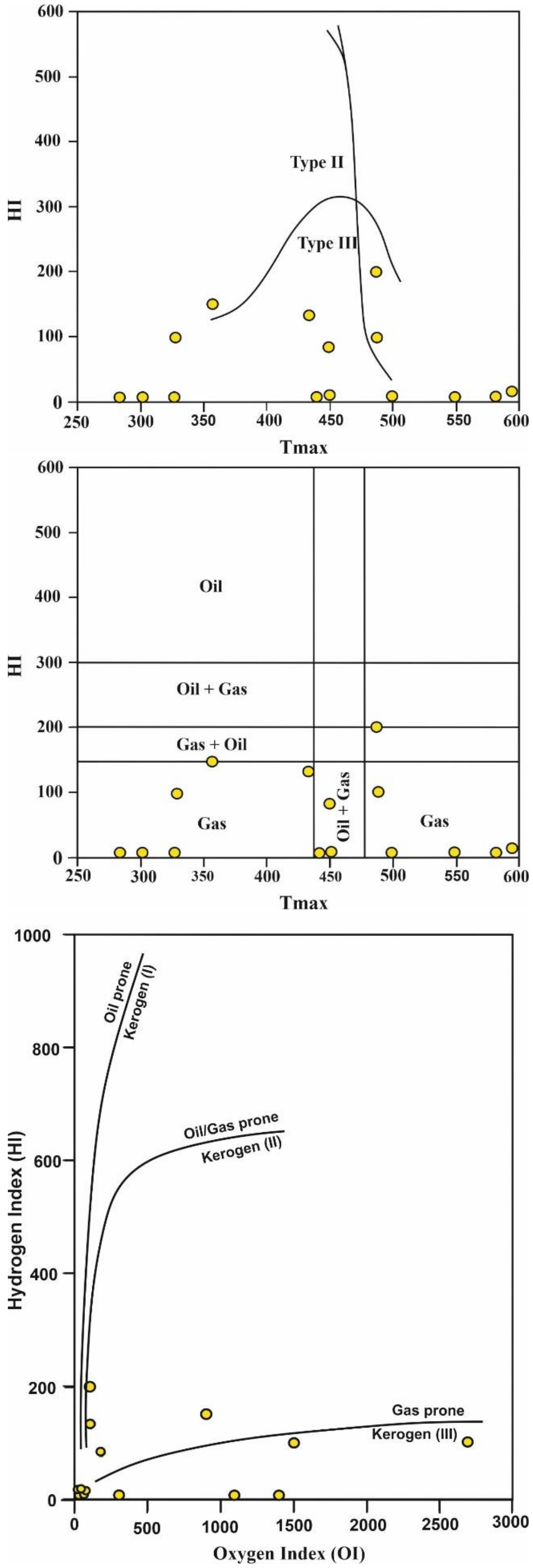


Fig. 6: (a) HI vs Tmax plot indicating kerogen type, (b) HI vs Tmax plot indicating whether it is gas prone or oil prone source rock, (c) HI versus OI plot showing the type of kerogen, and (d) HI vs Tmax plot showing the maturity level of kerogen

as well as postmature organic matter. HI value for most of the samples is less than 100 mg HC/g TOC with an average value of 52.5 indicating a gas generative type of kerogen (Type III). The geochemical data obtained from rock eval pyrolysis have been plotted on the kerogen classification diagram (Fig. 6c) where HI is plotted against OI in the Pseudo Van Krevelen diagram (Van Krevelen, 1961; Tissot et al., 1974) for delineating kerogen type and it suggests the abundance of Type III (gas prone) organic matter. The Tmax values of these rocks range from 283 to 595 °C, which suggests immature to postmature gas generation stage. Although some of them fall under the immature field and some others in the postmature or overmature organic matter in the HI vs Tmax plot (Fig. 6d), only three of them falls in the mature field. The HI vs Tmax is also plotted for kerogen type and for identifying oil prone/gas prone source rock (Fig. 6a and 6b), which indicates mainly type III kerogen and mostly gas prone source rock. The Oxygen Index (OI) results for samples with less than 0.5 wt.% TOC may be anomalous due to carbon dioxide or oxygen adsorption (Nuñez-Betelu and Baceta, 1995). So, both the HI vs OI and HI vs Tmax diagrams provides a reliable comparison of results that helps detecting the anomalies.

DISCUSSION

MINERALOGICAL COMPOSITION OF SANDSTONES

The studied sandstones are moderate to poorly sorted and are medium to fine-grained. The effect of mechanical compaction is quite evident from the sutured and straight contacts between grains, corroded quartz grains and alignment of the grains to each other. Monocrystalline quartz is abundant and is the main detrital component with relatively lesser amount of polycrystalline quartz indicating a cratonic or recycled source (Al-Harbi and Khan, 2008; Bordoloi et al., 2022; Chutia et al., 2019). Potassium feldspar is more abundant than plagioclase feldspar. Lithic fragments include mainly sedimentary with minor amount of igneous and metamorphic fragments, chert and trace amounts of heavy minerals. Detrital clay and calcite are mainly present as pore lining and grain coating cements. The relatively lesser amounts of feldspars and lithic fragments in these sandstones also indicates a cratonic source as well as a moderate degree of chemical weathering (Chutia et al., 2019; Bordoloi et al., 2022). In addition to this, smectite, illite and kaolinite are the main clay minerals found in the studied rocks as indicated by the X-Ray diffractograms (Fig. 5a). The porosity and permeability of sandstones with moderate sorting and varying grain sizes are expected to be lower, which has an impact on the reservoir parameters. Based on the petrographic study, these sandstones exhibiting sub-rounded to sub-angular shapes have undergone extensive reworking as indicated by the transportation history, which reveals that the source of the sediment is cratonic or recycled (Al-Harbi and

Khan, 2008; Bordoloi et al., 2022; Chutia et al., 2019).

DIAGENESIS AND RESERVOIR CHARACTERISTICS OF SANDSTONES

Numerous parameters affect the quality of sandstone reservoirs including (i) depositional porosity and permeability governed by grain size, sorting, and grain morphology, (ii) degree of mechanical and chemical compaction, and (iii) quantity and kind of pore filling cement (Worden and Morad, 2000). The most important diagenetic processes that have an impact on reservoir quality include cementation, dissolution, compaction and clay mineral authigenesis. Diagenesis is significantly governed by depositional environment and the diagenetic changes that occur during post depositional processes greatly control the distribution of porosity in sandstone reservoirs (Olaussen et al.,1984). The sandstones of the Geku formation have undergone diagenesis leading mainly to reduction of feldspars and unstable lithic fragments forming new clay minerals. Carbonate cement is more abundant than other cements and are the main cause of permeability and porosity reduction (Akinlua et al., 2016; Al-Ramadan et al., 2012; Shar et al., 2021). Calcite cement has the tendency to fill the intergranular pore space thereby affecting the reservoir quality. Calcite is present as patchy cement as well as poikilotopic cement in the intergranular pore spaces. Mechanical compaction is one such diagenetic process that begins right after the sediments are deposited and continues throughout the entire diagenetic history of the rock (Worden and Burley, 2009). Mechanical compaction appears to have very significant effect on these rocks as evident from the sutured and concavo convex grain contacts. The sandstones have undergone strong mechanical compaction, because of which most of the primary pores have disappeared. There has been observed an absence of secondary porosity indicated by the presence of abundant calcite and argillaceous cements. Compaction has also led to the deformation of lithic fragments and micas resulting in further loss of porosity in sandstone. Though it's possible that pseudoplastic deformation and the creation of a pseudomatrix can increase the development of secondary porosity but the low percentage of lithic grains in the studied sandstones did not significantly contribute to the formation of secondary porosity (Ramadan et al., 2004).

The studied sandstones of Geku Formation have undergone phyllomorphic / mesogenetic stage of diagenesis as indicated by the diagenetic changes observed during petrography such as precipitation of cements, sericitization of feldspars, authigenesis of secondary minerals such as chert, mica and quartz overgrowths all of which are responsible for porosity reduction (Dapples, 1962; Chima et al., 2018). Sandstone porosity is reduced by quartz cements, which form as syntaxial, euhedral grain overgrowths that frequently interlock within pores (Borgohain et al., 2010; Shar et al. 2021). Also, the concavo-convex and line contacts, which later forms sutured contacts between grains during increased stages of burial also suggest mesogenetic stage. The mechanical compaction as a result of increased burial during diagenesis indicated by bending of mica flakes substantiates a similar stage of diagenesis. And these processes have greatly affected the reservoir quality of the studied sandstones. Leaching or sericitization of feldspars does create secondary porosity but when it is in minor amount just like in the studied sandstones, it doesn't seem to play a significant role in porosity development. Cement types identified are mainly calcite, clay and silica (in the form of quartz overgrowths). Low porosity sandstones contain either abundant authigenic kaolinite in isolated secondary pores or widespread carbonate grains and cement that have undergone little or no dissolution (Goodchild and Whitaker, 1986; Pitman et al,1989; Al-Ramadan et al, 2012). In areas where fractures are filled by carbonate cement, the carbonate may act as a barrier to fluid flow and greatly reduce permeability.

The variations in grain sizes and sorting leading to lower porosity and permeability in sandstones is also controlled by the sediment's transportation history (Akinlua et al., 2016). The degree to which the sediments were transported, however, is what distinguishes these variations (Hussain et al., 2006). Generally, well rounded and sorted grains indicate that the sediments were transported for a long distance from its source, whereas the sub-rounded and poorly sorted grains imply short distance of transportation (Hussain et al. 2006). Earlier studies suggest recycled orogenic and craton interior sources with quartzose recycled and transitional recycled type sources for sandstones of Geku Formation (Chutia et al., 2019; Bordoloi et al., 2022). This is indicated by the sub- rounded and sub-angular grains, the abundance of monocrystalline quartz and minor amounts of feldspar and lithic fragments. The minor amount of feldspars is attributed to the diagenetic processes that the rocks have undergone leading to the formation of clay cements, which in turn have reduced the porosity and permeability of these rocks. Because clay and calcite obstruct the build-up and flow of fluids in pore spaces, they completely negate the potential of a good reservoir. It is important to note here that the Geku Formation belongs to continental facies and have been intensely deformed by post rift tectonics due to the WNW-ESE compressional force which was created when the Indian plate started colliding with the Burmese plate, as evident from the numerous folds and faults present in the study area. Since rifts with marine fills are more prolific hydrocarbon reserves than those with non-marine rifts with little or no post tectonic deformations, so the Geku Formation sediments might have limited distribution of good seals and the absence of seals in turn might have prevented the hydrocarbon accumulations thereby affecting their reservoir quality.

SOURCE ROCK POTENTIAL OF SHALE

The ability of a source rock to generate hydrocarbons is determined by the quantity (TOC), quality (Hydrogen Index) and maturity of kerogen present in the rock (Hunt, 1995). It has been found that rocks containing organic matter significantly influenced by continental sediments has very little contribution to oil generation potential due to the abundance of hydrogen poor organic matter (Gordon, 2021).

Rock eval pyrolysis has been used to determine the organic matter type, their distribution, hydrocarbon potential and the source rock type. The quantity and maturity of organic matter are expressed as TOC and Tmax, respectively. In general, Tmax values lower than 435 ºC indicate immature organic matter (Nuñez-Betelu and Baceta, 1995). TOC and Tmax values obtained for the studied rocks indicate immature to mature to postmature organic matter. Standard plots of Rock-Eval pyrolysis data have been used to determine source rock richness, quality, maturity and kerogen type.

Maturity stage determination plot of HI vs Tmax indicates mostly immature or post mature organic matter barring three samples, which falls in the mature field with Tmax values 486 °C, 488 °C, and 499 °C. Yinkiong shales are mainly oil/gas prone and gas prone (GP). On the assessment of GP (Generation Potential), all samples show poor potentiality for generating hydrocarbons. When compared to the pyrolysis of pure kerogen, low TOC samples from whole-rock pyrolysis frequently have lower HI and greater OI values (Hunt, 1995). This is worsened by the presence of smectite and illite (Fig. 5b) in immature low TOC rocks as the hydrocarbons, which released during thermal cracking of kerogen is adsorbed on clay mineral surfaces. A portion of the carbon in S2 never leaves the rock due to the adsorption of oil on clay minerals, which causes subsequent cracking to gas at higher temperatures (Hunt 1995). For shales, usually a TOC of 2.0% is considered to be good, and a TOC value higher than 4% is considered as very good (Nuñez-Betelu and Baceta, 1995; Espitalie et al., 1985). The studied rocks containing TOC averaging 0.09% indicates poor organic richness.

The generation potential of source rock can be delineated using the pyrolysis data. According to Hunt (1995), source rocks with GP <2, 2 to 5, 5 to 10, and >10 are considered to be poor, fair, good and very good, respectively (Espitalie et al., 1985). The average generation potential of the studied shales is 0.02. Hence, the generation potential of shales of Geku Formation is poor. The Production Index (PI) is also in part indicative of the degree of thermal maturity. In general, PI values below 0.4 indicate immature organic matter; PI values between 0.4 and 1.0 indicate mature organic matter; and PI values above 1.0 are indicative of overmature organic matter (Nuñez-Betelu and Baceta, 1995; Espitalie et al., 1985). The PI value of the studied shales ranges from 0.13 to 1.0 which indicates immature to mature as well as postmature organic matter.

The amount and type of organic matter preserved in sediments is controlled in part by the depositional environment but also by the productivity of the waters, sediment grain size, physical conditions in the area of deposition, and mineralogy of sediments. Sedimentary rocks deposited in deltaic environment tend to have low TOCs and mostly exhibits type III kerogen with some type II, which is most likely to produce gas rather than being an oil source (Hunt, 1995). Also, the type of organic hydrogen is controlled by the nature of the organic matter. The low hydrogen content (HI) and a variable high oxygen content (OI) indicates that the organic matter is derived from terrestrial sediments (Nuñez-Betelu and Baceta, 1995; Hunt, 1995). Rocks containing immature kerogen with TOC < 1% and HI values 150-400 indicate terrestrially derived organic matter (Davis et al., 1989). These data coincide with the results obtained from pyrolysis of shales of Geku Formation in the present study. Type III kerogen corresponds to terrestrially produced organic matter, especially material from higher plants. Terrestrial organic matter has a low HI value, because of its nature and damage it suffers during transport. Instead of being an oil source, this sort of kerogen typically produces gas (Nuñez-Betelu and Baceta, 1995). The most common form of organic matter decomposition is oxidation. In contrast to fresh core samples, outcrop samples often have lower HI values and higher OI values due to the removal of hydrogen and addition of oxygen during oxidation (Nuñez-betelu and Baceta, 1995). Generally, surface samples always appear with low TOC and other rock eval parameters. Considering this, it is believed that the Geku shales of the study area negates all the geochemical parameters of being a good oil prone source rock and can effectively act as Type III gas prone source rock, which is capable of producing gas.

CONCLUSION

The integrated petrographic and rock eval pyrolysis study of sandstones and shales of Yinkiong Group, the following conclusions can be drawn:

1. The Geku sandstones are mainly fine to medium-grained, moderate to poorly sorted quartz arenite and quartz wacke, which have suffered porosity loss due to precipitation of mainly calcite cement.

2. The studied sandstones are texturally immature to sub-mature as reflected by their grain size, particle shape, and degree of sorting, which contributed to their poor reservoir quality.

3. The sandstones have undergone strong mechanical compaction as evident from the long,

concavo-convex and sutured grain contacts responsible for their porosity reduction.

4. The source rock characterization of Geku Shale suggests Type III kerogen, suitable for gas production. All the samples are organic poor and do not constitute a potential source rock. Only small amounts of gas may have originated from these rocks.

5. The low hydrogen content (HI) and a variable high oxygen content (OI) indicate that the organic matter is derived from terrestrial sediments.

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DECLARATION OF CONFLICTING INTEREST

The authors declare that they have no competing interests in this manuscript.

AUTHOR CONTRIBUTIONS

All the authors were actively involved in the field study for the proposed work. AB carried out the petrographic study, analysed the data and drafted the manuscript. AC helped supervise the experiment, analysis and interpretation of results. CDT edited and coordinated the manuscript. All authors reviewed the results and approved the final version of the manuscript.

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