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Thermally Altered Coals from Bore Core EBM-1, East Bokaro Coal Field, Damodar Valley, India: A Petrographic Inference

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Abstract: Petrographic analysis of the coals from bore core EBM-1 of East Bokaro Coalfield revealed characteristic changes as a result of thermal alteration by an intrusive body. The enhancement of 'rank' (increase in the VR_r% values) is observed in the heat affected coal in the lower part of the bore core. The vitrinite in the coal at a depth of 984.95 m showed devolatilization vacuoles and initiation of mosaic structure due to heat alteration, dessication cracks and micropores. Meta-liptinite having reflectance value higher (1.67%) than that of the host vitrinite (1.09% - 1.36%) was also recorded. Bi-reflectance values of the un-altered coals were normal in the range of 0.06% - 0.09% where as the altered coal at a depth of 984.95 m showed an abnormal increase in the values (0.23%). Presence of secondary injected mineral matter and char particles further indicate the effect of thermal alteration. Palynological investigation of both altered and un-altered coal reveals that the palynomorphs recovered from the altered coal are dark and opaque due to the charring effect while the palynomorphs from un-altered coals exhibit a clear internal structure and can be easily identified.

Keywords: Coal petrography, Thermal alteration, East Bokaro coalfield, Bi-reflectance, Muditoli block.

INTRODUCTION

During coalification, the rank of coal directly depends on the depth of burial (Hilts Law) and temperature of burial unless they are subjected to igneous intrusions. These intrusions bring about anomalous change which is evident in the rank and maceral composition of coals. In the recent past, these changes have been studied by various workers. Petrographic investigations on east Bokaro coals were carried out by many workers viz., Mukherjee and Bhattacharya (1961, 1963), Casshyap (1964), Pareek (1977), Navale (1978), Moitra et al., (1993) and recently by Singh et al., (2007). Heat induced changes in the coals near thrust zones were studied by Anand Prakash (1992) and Ghosh (1997) where as a number of studies have been done on thermally altered coals from India (Chandra and Srivastava, 1980; Chandra and Taylor, 1982; Pareek, 1988; Singh et al., 2007, 2008; Sarana and Kar, 2011 etc).

The current study is an attempt to petrographically identify the signatures of thermal contact (igneous intrusion) in coal collected from boreholes. Palynomorphs were also studied from the samples to infer the effect of heat on their optical characters.

STUDY AREA

The east Bokaro coalfield is one of the major repositories of medium-coking coal in the peninsular Gondwana basins of India. It occupies an area of about 237 sq. km between latitudes 23º 44' N and 23º 49' N and longitudes 85º 42' E and 86º 04' 30" E. The coal field contains a number of thick and thin seams belonging to Barakar and Raniganj formations. The coal seams of the study area are associated with sedimentary succession from Talchir to Supra-Panchet (Mahadeva) formations.

Scattered exposures of Talchir Formation unconformably overlie the basement rocks in the northeastern part of the coalfield around Chapri area and to the west of Gomia, in the northwestern part of the coalfield. The eastern part of the basin is occupied by Barakar Formation, whereas, the crescent-shaped outcrops of the Barren Measures are exposed in the central and western parts.

Successively overlying Raniganj and Panchet formations also follow the same crescent pattern further towards west. Supra-Panchet Formation, occupying the higher elevation in Lugu Pahar at the westernmost part of this coalfield, shows an angular unconformity with the underlying Panchet

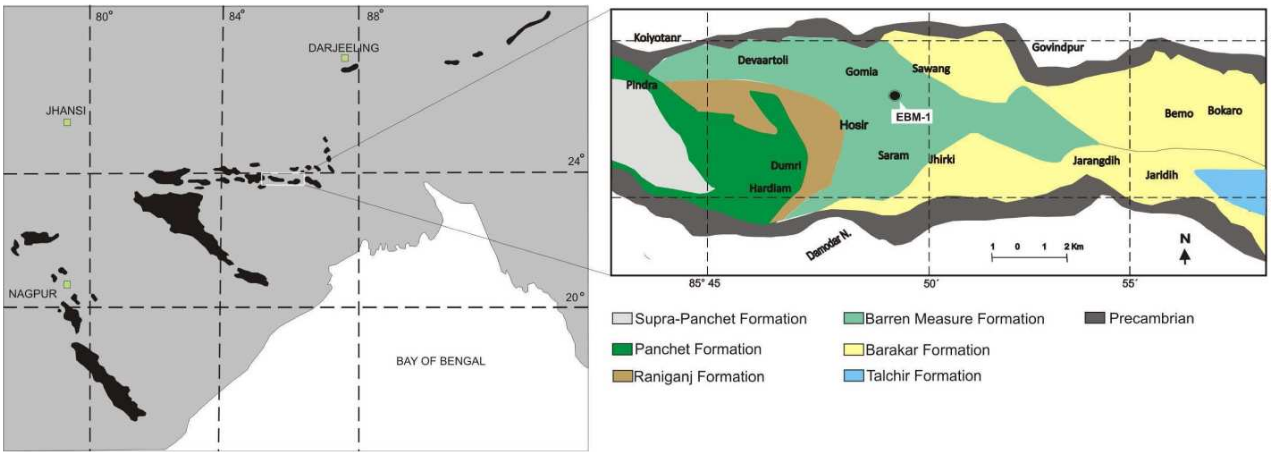

Fig.1. Location map of East Bokaro coalfield, Damodar Basin and bore hole EBM-1.

Formation. Panchet Formation shows both overlapping and faulted relationships against the southern basement. To the south of the Tenughat reservoir (latitude: 23º452 N; longitude: 85º50' E), the southern limb of Barakar Formation is attenuated against the southern boundary fault. To the north and northwest along the margin of the coalfield, the Barakar strata occurs as narrow, elongated, detached and faulted wedges / slices against the basement rocks, Barren Measures and Panchet formations (after C.S.Raja Rao, 1987).

Muditoli Block

Muditoli Block is situated in the western part of the east Bokaro coalfield where only the rocks of the Barren Measures are exposed on the surface (Fig.1). Barakar coal seams are intersected beneath the thick cover of the Barren measures. The general strike of the beds is NNW-SSE with 12° to 17° dip towards southwest. The bore core EBM-1 was drilled on the northern bank of Bokaro river, on the south-eastern part of the Muditoli block. The bore core has a lithology of sandstones, shaly coal, shale and coal (Fig.2). A lamprophyre intrusion has been reported in this block, which has enhanced the 'rank' of certain coal seam (Roy and Chatterjee, 2010).

Coal Seams in Muditoli Block

The Barakar Formation in Muditoli block hosts 25 thick and persistent regional coal seams along with five local ones. These seams vary in thickness from 0.34m to 19.10 m.

The pattern of development of these seams in the western part of the coalfield significantly differs from central and eastern parts. The coal seams/sections in the block are low in moisture (<2%), medium coking and clean in nature. Overall ash content varies from 13.00% to 47.90%, Volatile Matter from 12.40% to 28.90% and Fixed Carbon (FC) varies from 30.50 % and 64.30% (Roy and Chatterjee, 2010).

METHODOLOGY

For petrographical studies 7 representative core samples of coal were collected from bore core EBM-1. Recommendations of ISO 7404-3, 1984; ISO 7404-5, 1984 and ISO 7404-2, 1985 have been followed in the sample preparation and observation. The samples were crushed to -20 mesh size fraction and pellets were prepared by embedding them in a mixture of epoxy resin and hardener in a ratio of 5:1 respectively. The hardened pellets were ground with different grades of silicon carbide paper and further polished with polishing alumina and used for the study as per specifications. The reflectance was measured on vitrinite (collotelinite) constituent on Leica DM4500P microscope using Sapphire (0.594) and Yttrium-Aluminium-Garnet (0.904) as reflectance standards, immersion oil with RI 1.518 and 100x objective lens. PMT III and Software MSP 200 was used to take the measurements and for calculation. The maceral analysis was carried out in fluorescent mode on the same microscope. Leica application suite (LAS) was used for acquiring image. Quantitative estimation of macerals was done on 400 counts per sample counted on automatic point counter using Petroglite 2.35 Software.

For palynological studies the samples were macerated using standard maceration techniques treating the crushed sample of 1mm particle size with HCl to remove the carbonates and HF to remove silicates and liberated the organic matter. Further the samples were treated with HNO_3 to digest the humic matter and release the palynomorphs from the organic debris. The organic residue was mixed with polyvinyl alcohol and canada balsam was used as mounting media to prepare permanent slides.

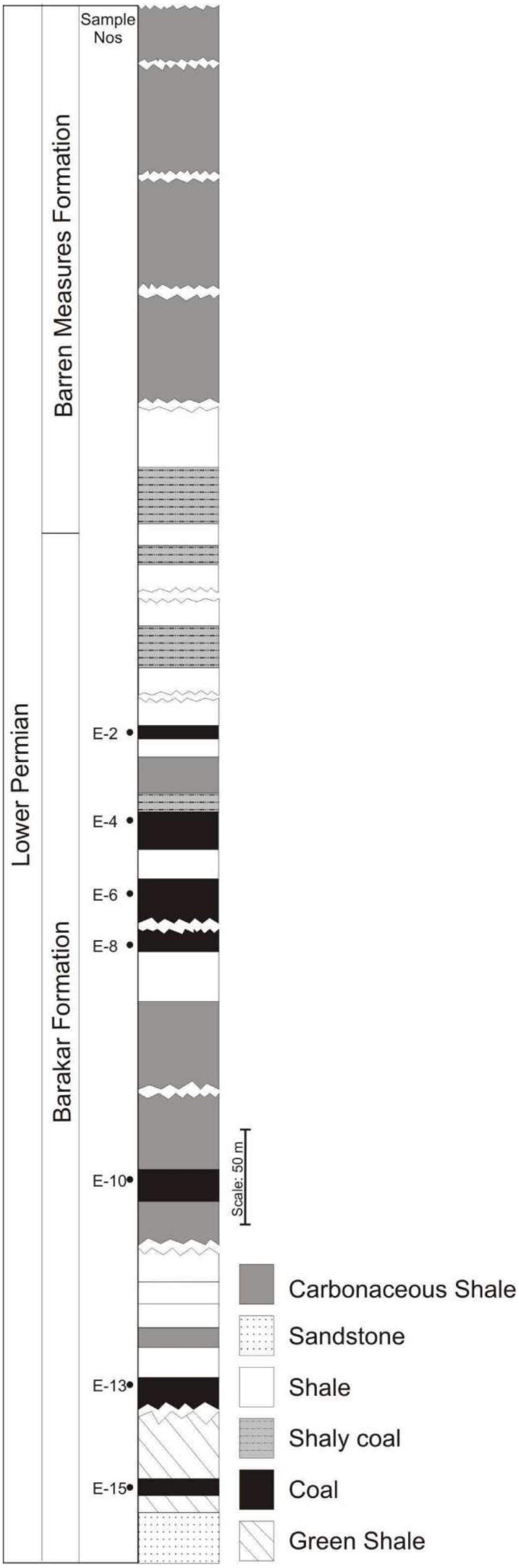

Fig.2. Litholog of bore core EBM-1.

RESULTS AND DISCUSSION

Rank

Vitrinite reflectance measurement is the most effective method of evaluation of coal rank other than geochemical method. In many bore cores of east Bokaro coalfield the variation in rank is observed which may be due to the extensive effect of igneous intrusive bodies, both dykes and sills of mica peridotite (Mishra et al., 1998). Apart form these the coalfield is affected by a network of intra basinal faults which impart a complex structural character (GSI, 1987). Considerable variations in vitrinite reflectance have been noticed in the coals recovered from bore core EBM-1 at various depths which is due to depth and subsequent pressure while anomalous enhancement of 'rank' is attributed to contact thermal alteration which is observed in sample E-13 with 1.36% R_o at a depth of 984.95 m (Fig.3). It's over lying (E-2, E-4, E-6, E-8 and E-10) and underlying coals (E-15) show a slight decrease in reflectance values (R_r range 0.90%-1.12%). This anomalous increase in rank associated with characteristic thermal alteration features observed, indicates a possible igneous intrusion. The vitrinite random reflectance values for the studied coals range from 0.96% -1.36%. The coal at the depth of 469.35 m has a VR_r value of 0.96% bringing it under the high volatile bituminous rank. The VR_r of coals, from a depth of 540.05 m to 1142 m, range between 1.09% - 1.36% suggesting Medium Volatile Bituminous stage of coal rank (ASTM). The VR_r value of the present study correlates with the VR_r data of other bore holes from east Bokaro coalfield published by Mishra et al., (1998).

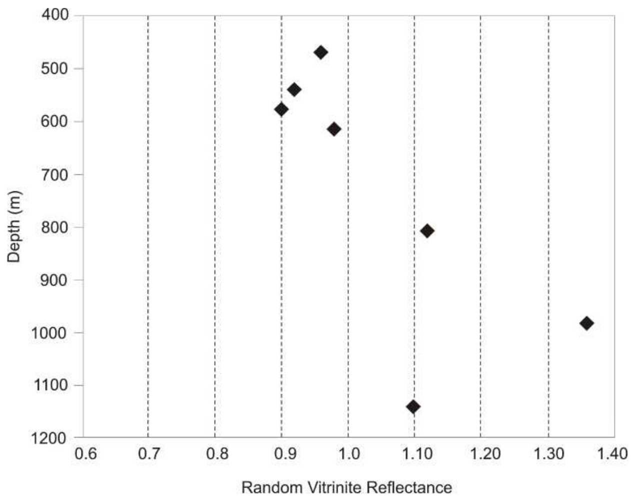

Fig.3. Depth versus Rank (vitrinite random reflectance) plot of the studied coal samples.

Bi-reflectance

Bi-reflectance is a measure of reflectance anisotropy of vitrinite, which is normally caused by the progressive orientation of the aromatic nuclei into the bedding plane as a consequence of load pressure (Taylor et al., 1998). This is determined using polarized light and the rotation of the angle of measurement (Ruiz and Ward, 2008). Methods for obtaining these parameters were developed by Ting and Lo (1978) and Ting (1978) and later modified by Kilby (1998, 1991) and Duber et al (2000).

The bi-reflectance values of the studied coals range from 0.06% to 0.09% for samples E-2 (depth 469.35 m), E-4 (540.05 m), E-6 (577.70 m), E-8 (616.15 m) and E-10 (807.90 m) while the values for samples E-13 (984.95 m) and E-15 (1142.00 m) are 0.23% and 0.11 % respectively, suggesting possible proximity of these seams to the intrusive body (Fig.4). Sample E-13 with a VR_r of 1.36 has the highest bi-reflectance value further supporting the fact that bi-reflectance increases with increase in rank (Ruiz and Ward, 2008).

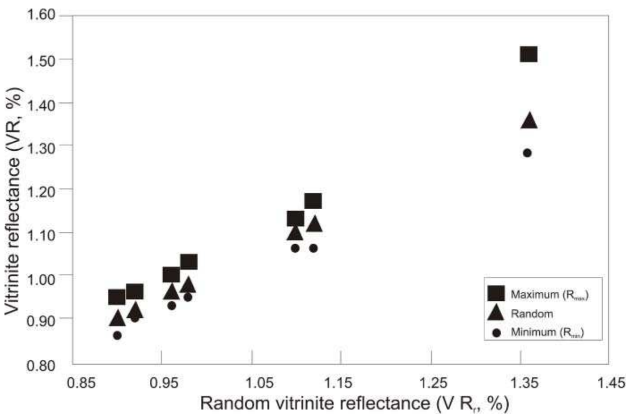

Fig.4. Bi-reflectance values for the studied coal samples. Notice the high anisotropy displayed by thermally altered sample.

Maceral Composition

The coal samples were studied under reflected light and fluorescence mode to identify and categorize the macerals. Point counting was carried out to obtain the relative frequency of individual maceral (Fig.5). The basal part of bore core EBM-1, samples E-13 and E-15 show the dominance of liptinite (40.4 vol %-51.3 vol. %) and sub dominance of vitrinite (32%.vol-38.4%.vol) followed by inertinite (6%.vol-14.6%.vol) maceral group with 6.6% - 14.6%.vol. mineral matter. The overlying coal bands (samples E-2, E-4, E-6, E-8 and E-10) are comparatively rich in vitrinite (35%-44.8%.vol) sub-dominated by liptinite (24%-40%.vol) and inertinite (11%-20%.vol). Liptinite in these samples is characterized by well preserved megaspores and microspores albeit in fewer proportions (fig.6, A-B). Mineral matter is relatively high in the upper section of the bore core ranging from 11.3%-17.5%. Vitrinite group of macerals occur as thick bands and isolated grains with grey colour. The fractured collotelinite bands/grains show expulsion of hydrocarbons in some samples. Liptinite group of macerals are found scattered in the groundmass and are mainly dominated by liptodetrinite in the samples E-2, E-4, E-6 and E-8. Dominance of resinite is seen in samples E-10, E-13 and E-15. Resinite in coals is ascribed to plant resins and essential oils in leaves which are transformed through coalification to spherical or oval shaped bodies and infrequently to lenses or thin bands of fluorescing material (Bodily and Kopp, 1987). The resinite during coalification process at some point is relatively fluid as inferred by microscopic observations in the present study (fig.6, C-E). In samples E-10 and E-15, exsudatinite occur as veins of weakly reflecting but moderately to strongly fluorescing material indicating that the coal has expelled hydrocarbons (Fig.6, F). Inertinite occurs as isolated grains/cluster of oxidized cells often with well preserved cell structure. The bogen structure of semifusinite is observed in almost all samples. In all the fusinite and semi-fusinite, the cavities are filled with resinite and in some cases with exsudatinite (Fig.7). Exsudatinite is strictly secondary bitumen generated by hydrogen rich liptinite macerals during the coalification process (ICCP, 1971).

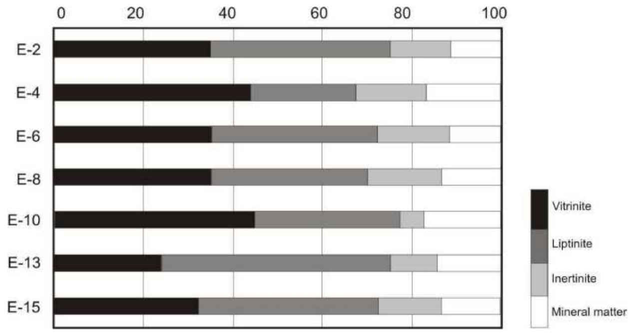

Fig.5. Frequency of macerals (vol.%) and mineral matter (vol.%) from the studied coals.

The maceral analysis of coals from the present bore core reveals that the liptinite maceral is mainly represented by liptodetrinite and there is an increasing trend in the percentage of resinite and exsudatinite with depth. Resinite in particular is found in larger proportion in samples E-13 and E-15 at a depth of 984.95 m and 1142 m respectively and at these depths no structured maceral is present.

Sample E-13 at a depth of 984.95 m has a high percentage of liptinite (51.3 % vol.) mainly resinite and has

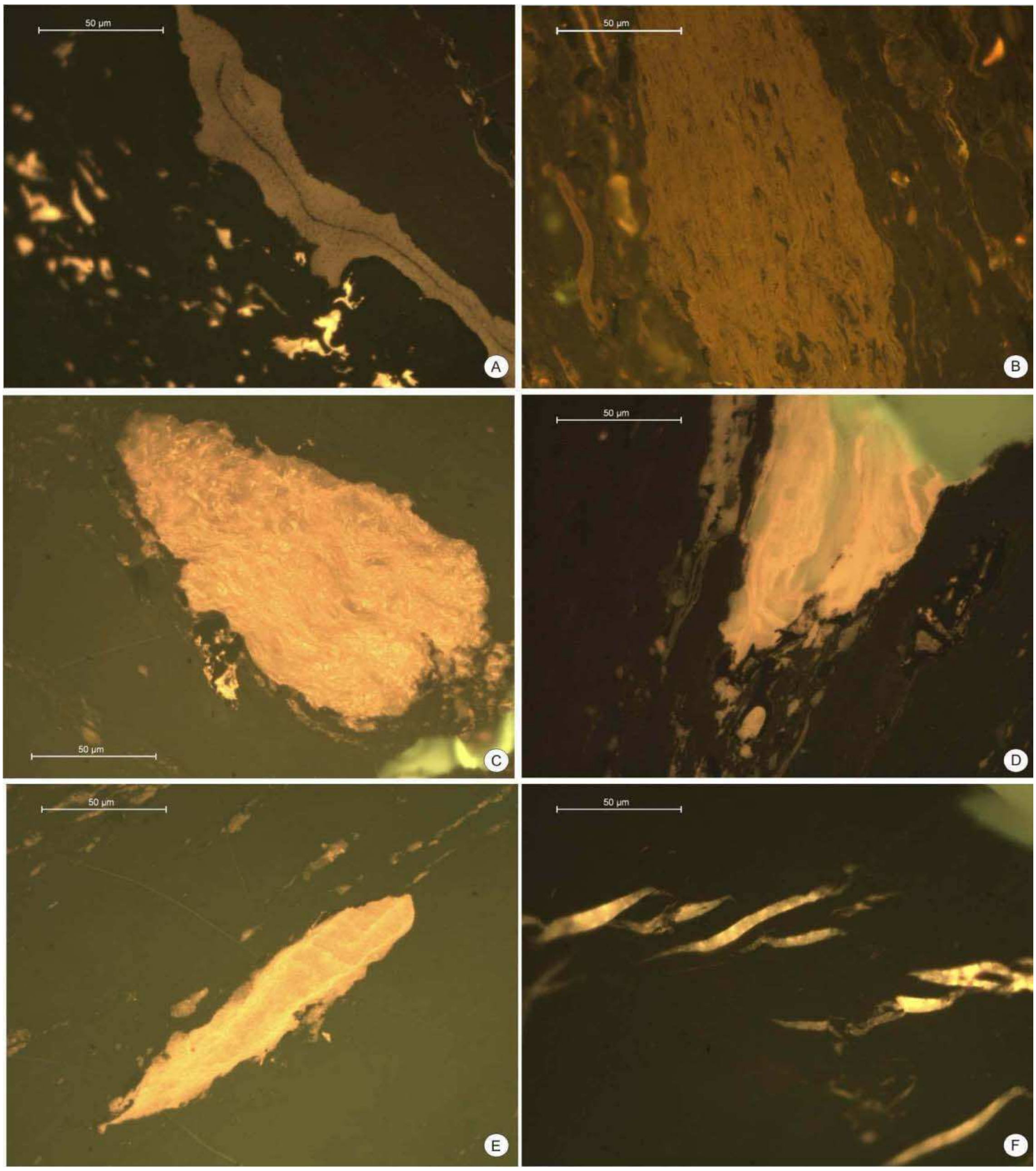

Fig.6. Liptinite macerals from un-altered coals (**A-B**). (**A**) sporinite (megaspore). (**B**). sporinite (cluster of microspores). (**C-F**) liptinite macerals from altered coals. (**C-E**) resinite. (**F**) exsudatinite.

an average random reflectance value of 1.36%. This clearly indicates that the effect of heat due to intrusion has surpassed the suppressive threshold in this particular sample where in the higher liptinite proportion has no effect on vitrinite reflectance as compared to usual circumstances due to absorption of thermally generated bitumen into the vitrinite (Gurba and Weber, 2001).

Mineral Matter

The visually observed mineral matter content of the studied bore core ranges from 2.9-17.5 % vol. Clay minerals and pyrite is found in few of the samples. Syngenitic framboidal pyrite derived from microbial sulfur reduction processes involving oxidation of organic matter (Taylor et al., 1998) is found in sample E-10 and infilterational pyrite filled in the cleats along with few disseminated pyrite is found in E-13 and E-15 (Fig.8, E-F). Sample E-8 and E-10 show abundance of quartz crystals (Fig.8, A) which are associated with detrovitrinite and inertinite particularly in fusinite. Calcite is found in E-13 and E-10 in high

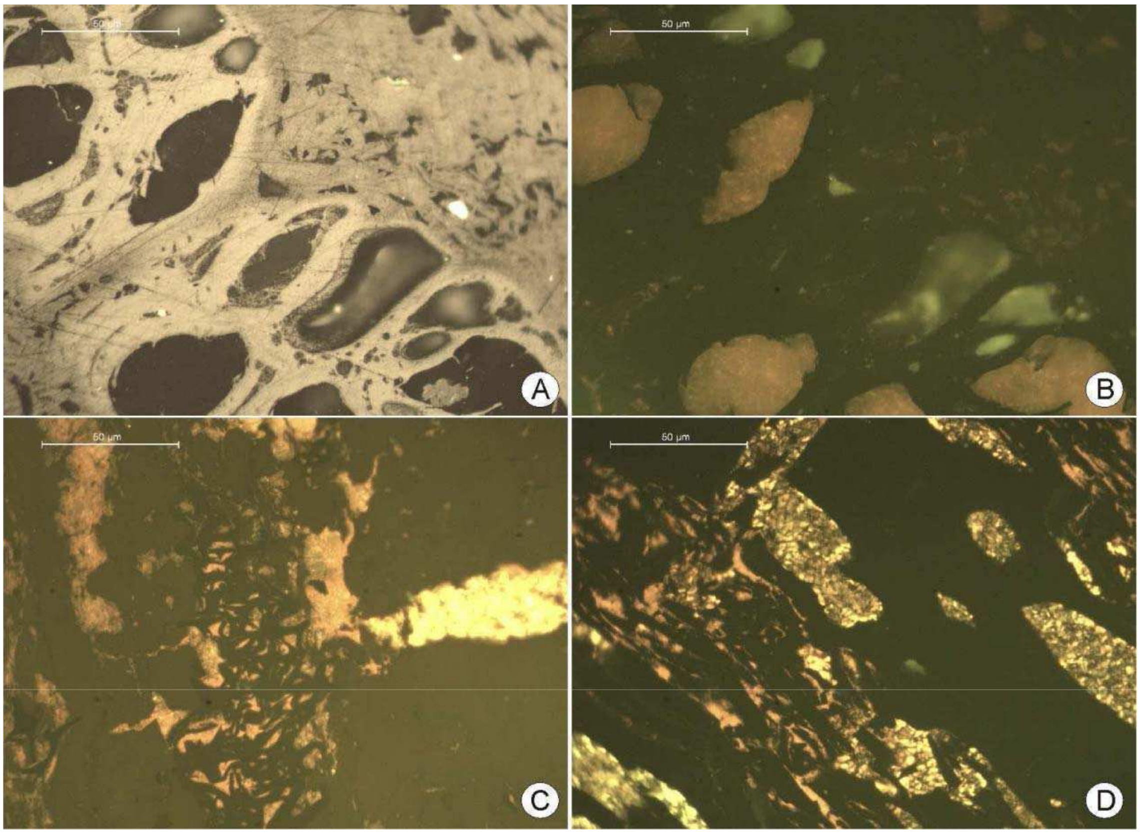

Fig.7. Cavity filling of exsudatinite. (A) semifusinite cavities filled with exsudatinite (Ex) appearing pitch black in white light. (B) same as (A) under fluorescence mode. (C-D) exsudatinite in cavities of fusinite.

proportions. Secondary carbonate infilling is basically restricted to collotelinite grains/bands as cleat filling (fig.8, C-D) and as cell cavity fillings of inertinite (fig.8, B). To ascertain the presence of calcite in cleats, the polished pellets were smeared with Alizarin Red – S indicator and after a few minutes the pellets were observed under the microscope and was noticed that the calcite in the cleats turned reddish brown.

Thermal Alteration Signatures

The evident change observed in the thermally altered coal from present study is the decrease of liptinite content and wherever present are optically indistinguishable.

Usually exsudatinite are rare or not seen in coals where vitrinite reflectance exceeds 0.8% because exsudatinite is lost as a normal part of the maturation process at higher ranks. But in the present study exsudatinite is found in fair amount in samples E-13 and E-15 suggesting that the reflectance values of vitrinite are enhanced by the intrusive body. *En echelon* offsets of exsudatinite veins are found in E-13 coal sample which also exhibit clear initiation of mesophase mosaic structure in vitrinites (Fig.9, A) due to intrusive heat. The intrusive stress on vitrinite is seen in coal sample E-13 resulting in a fracture in the grain and distortion of exsudatinite associated with it (Fig.9.C).

Mishra et al., (1998) noted that the western part of east Bokaro coalfield showed higher liptinite content which did not fluoresce, particularly in coals with vitrinite reflectance greater than 1.20%. In the present study the heat affected coals have liptinite macerals viz., sporinite and cutinite which are relatively identified by their outline but they do not show fluorescence. These liptinites are termed as meta-liptinites. Meta liptinite is also noticed in sample E-13 and E-15 which are found only in coals that have suffered contact metamorphism (Fig.9, G-H). The reflectance of the meta-liptinite (1.67%) was found to be much higher than the vitrinite reflectance (1.09-1.36%) and the presence of meta-liptinite is considered as an evidence for temperature induced changes due to contact alteration.

The presence of massive and framboidal pyrite in the heat affected samples indicate that the pyrite remained unaltered or the heat was not enough to induce further changes in them, as the studies conducted by Chandra and Taylor (1982) suggest that pyrite (FeS_2) changes to iron sulphide (FeS) and further to hematite in temperatures >500° C (Sarana and Kar, 2011). The stability of pyrite and de-

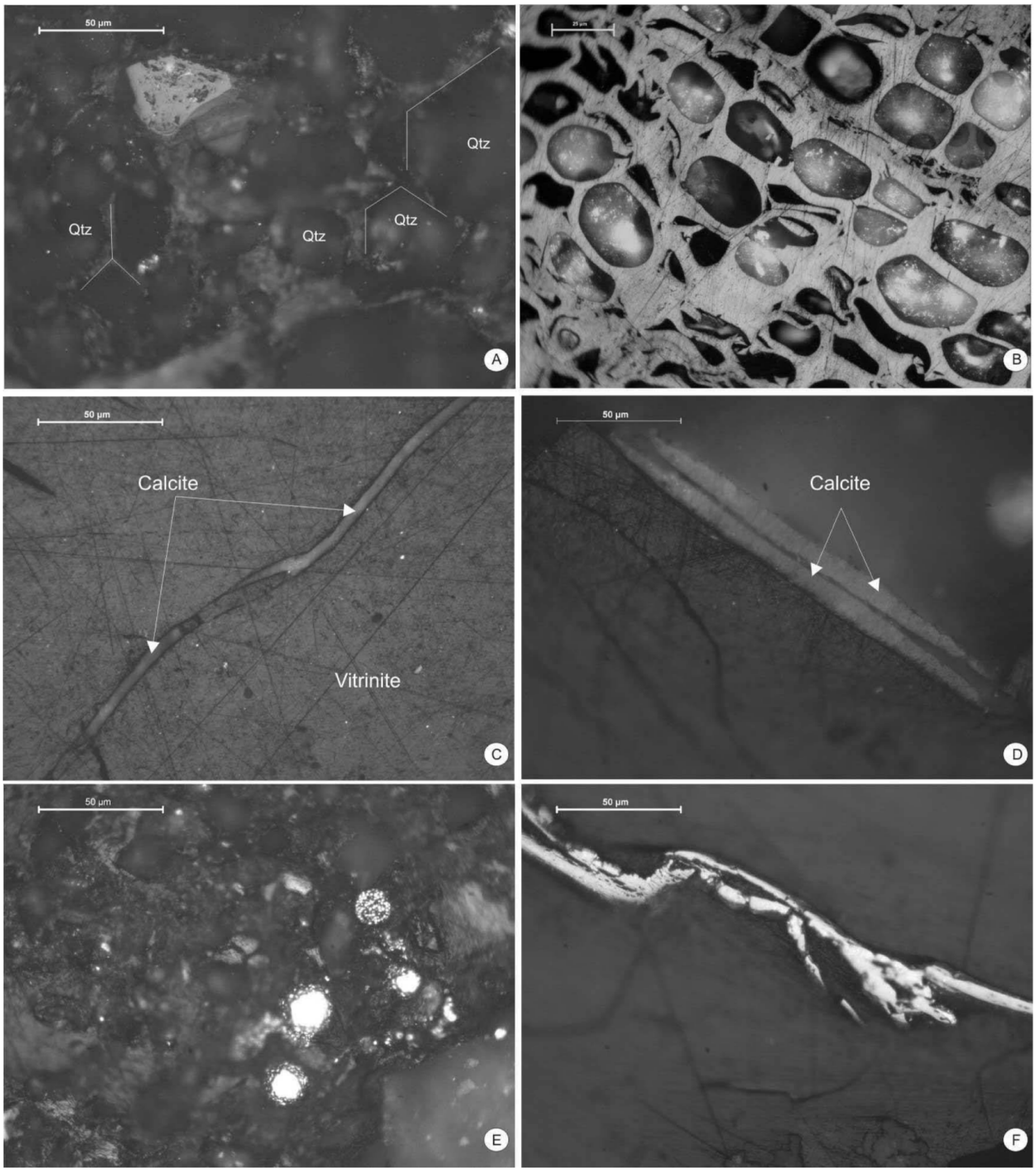

Fig.8. Mineral matter observed in the studied coals. (A). Quartz (notice the hexagonal crystal outline of quartz in detrovitrinite groundmass). (B) Calcite as lumen infilling in inertinite. (C-D) calcite as cleat filling in vitrinite. (E) framboidal pyrite. (F) infilterational pyrite in cleats.

polarization of structured liptinite maceral indicate that the temperature of thermal alteration of E-13 and E-15 coals was below 500° C.

Microscopic pores and vesicles are visible in the samples E-10, E-13 and E-15 (Fig.9, B). These structures indicate that the rapid devolatilization process has occurred in these coals. Yao and Liu (2012) stated that these changes are brought about by two process i.e., pyrolysis and carbonization. Pyrolysis involves the loss of coal as a result of thermal decomposition which results in the generation of gases leading to the formation of devolatilization vacuoles. These structures are prevalent in sample E-13 and E-15 along with 'Comma slits' and dessication cracks which are recorded in abundance. These microscopic structures indicate that the rapid devolatilization process by the heat caused by the intrusion (Amijaya and Littke, 2006) occurred in samples E-13 and E-15. The resinite found in the samples E-13 and E-15 show a strong yellowish orange fluorescence

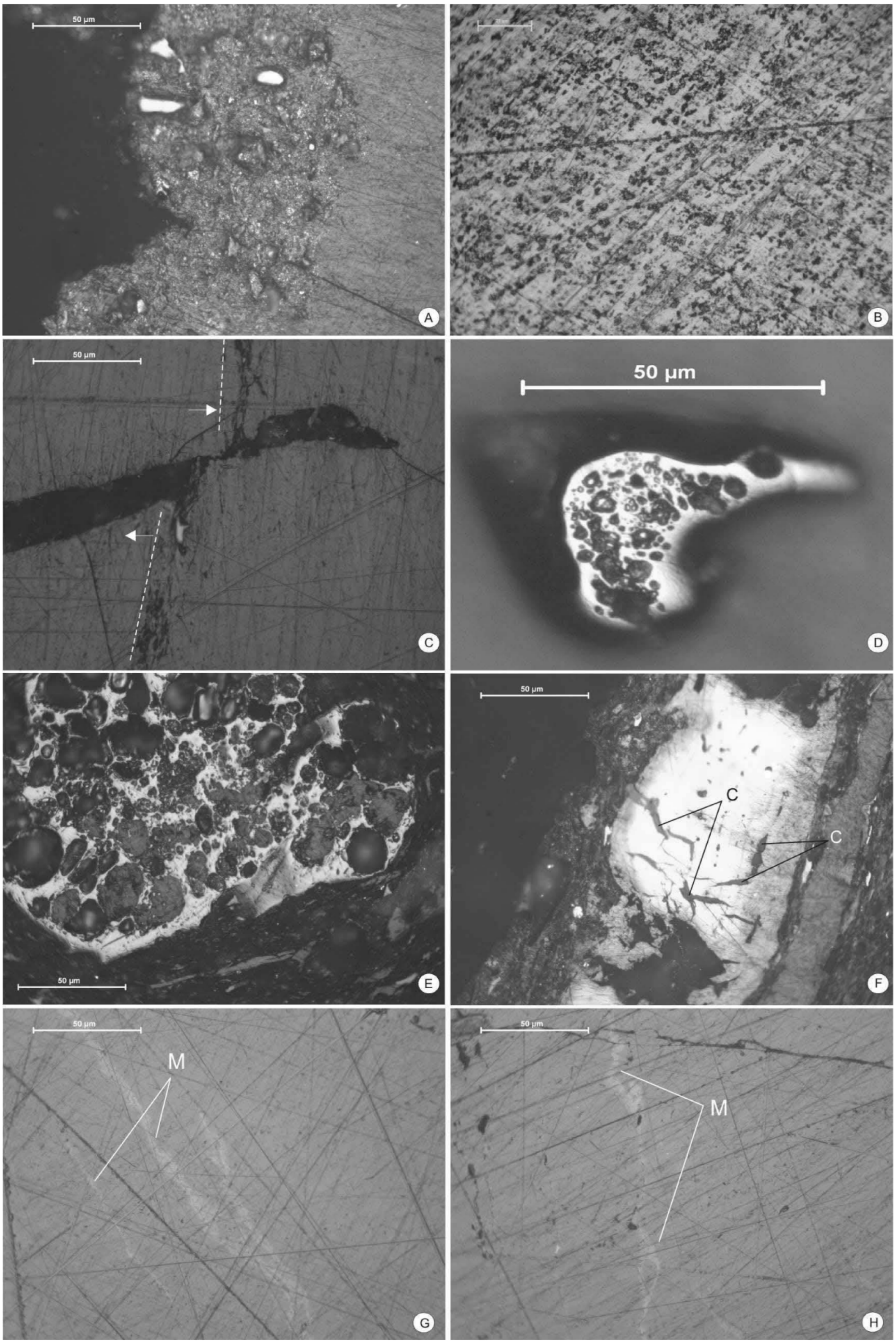

Fig.9. Characteristic thermal signatures in studied heat altered coals. **(A)** Initiation of mosaic structure. **(B)** Micropores in vitrinite. **(C)** Fracture perpendicular to exsudatinite vein in a vitrinite grain. **(D-E)** Char particles with characteristic pore structure. **(F)** Inertinite grain with secondary carbonate infilling in the fracture. **(G-H)** Meta-liptinite.

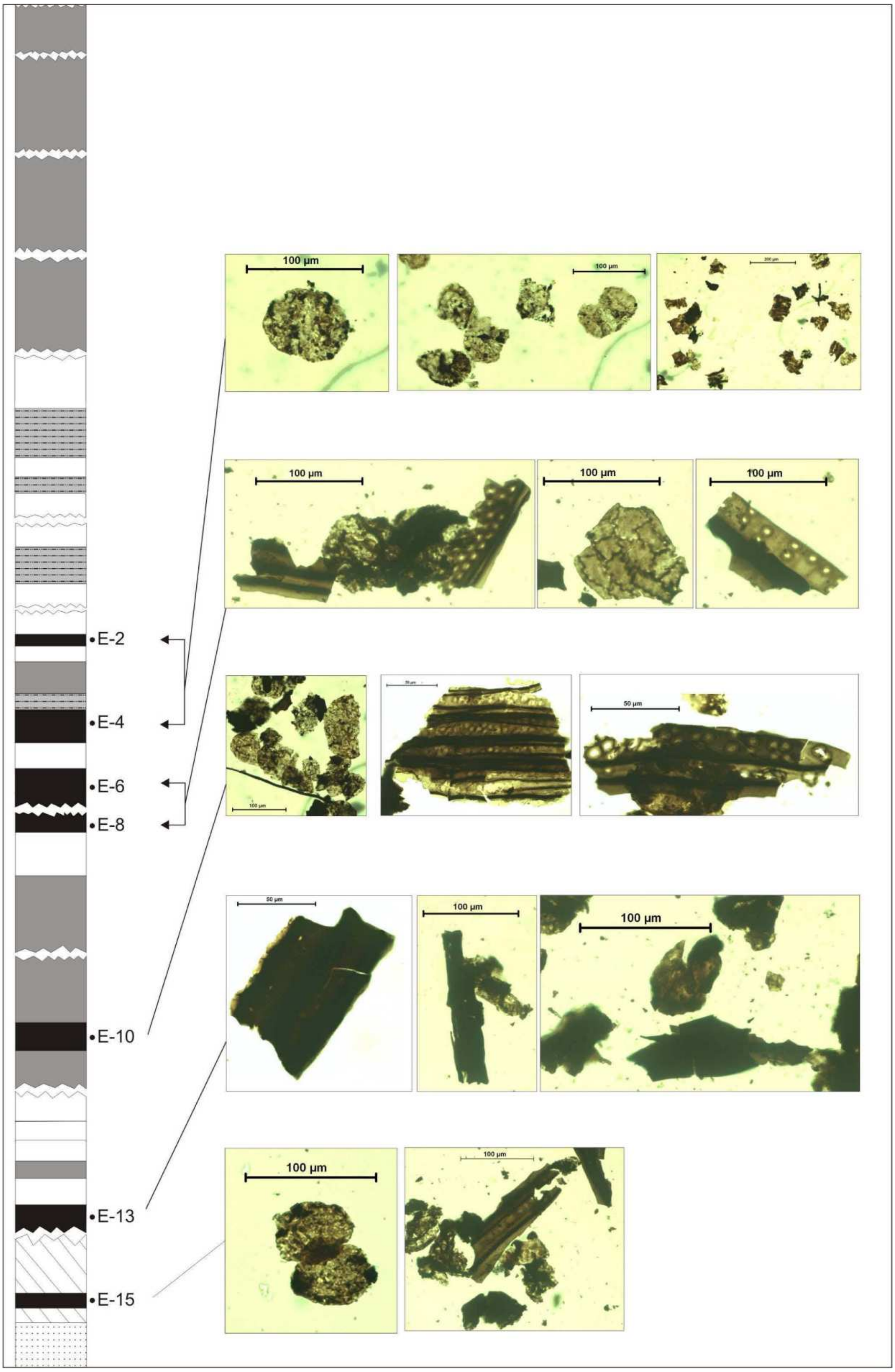

Fig.10. Palynomorphs recovered from the studied samples. note the variation in opacity of altered and un-altered coals.

and is usually associated with collotelinite in the form of cavity fillings.

The flow structure found in majority of the resinite particles indicates mobilization in liquid form and forceful injection into the cavities due to the heat generated by the intrusion. Certain fusinite grains in sample E-13 display cracks caused due to their inability to accommodate the stress generated by the intrusion and behave in a fragile way(fig.9, F) (Valentim et al, 2006). Char particles in E-13 (fig.9, D-E) have reflectance higher than the associated vitrinite and have characteristic degasification pores. A few un-altered macerals found along with the char particles indicate that these chars were formed due to the heat effect on coal by pyrolysis under conditions of slow heating rate (Kwiecinska and Petersen, 2004; Unsworth et al., 1991).

Palynological slides were prepared using standard maceration techniques to assess the effect of heat on the spore-pollen and phytoclasts. The spores retrieved along with opaque phytoclasts from the sample E-10, E-13 and E-15 show relative darkening of their exine. The tracheids and other structured phytoclasts in samples E-2, E-4, E-6 and E-8 are well preserved and are light brown to dark brown in colour with clearly visible internal structure (fig.10). The palynomorphs in sample E-10 is dark, blackish brown in colour and the phytoclasts are almost opaque with translucent edges/borders suggesting the end of intrusive heat effect at this depth. The clear effect of heat can be found in sample E-13 with a VR_r 1.36%. The palynological slides of E-13 shows opaque particles which cannot be distinguished as palynomorphs or phytoclasts.

CONCLUSIONS

The coal seams from different depths obtained from bore core EBM-1 were studied petrographically and palynologically to assess the effect of intrusive heat. Certain distinct characteristics can be observed which reflect the changes in the coal maceral composition and optical characters due to thermal alteration. The two coal samples E-13 and E-15 exhibit the characteristic features of thermally altered coals. The presence of resinite and exsudatinite in these samples signify that the heat was not sufficient to remove all the macerals of liptinite group. The relevant effects of the heat on the affected coal are summarized as follows:

- In the heat affected samples E-13 with a VR_r of 1.36% the conversion of coal to coke has not occurred but the warping of the structures of vitrinite, its reflectance and bi-reflectance is amplified.
- The effect of heat caused by intrusion can be observed in the sample E-13 at a depth of 984.95 m where in meta-liptinite is found whose reflectance is comparatively higher (1.80%) than the host vitrinite (1.36%) in which it is embedded.
- The increase in bi-reflectance value (0.23%) is noticed in sample E-13 at a depth of 984.95 m indicating the effect and proximity of the intrusion where the bi-reflectance values increase (Gurba and Weber, 2001).
- The elliptical fractures and dessication cracks are a result of the post-depositional stress caused by the igneous intrusion and the heat from this intrusion was responsible for the emplacement of carbonates and other minerals in the studied coal samples E-13 and E-15 at the depths of 984.95 m and 1142.15 m respectively.
- Few coke grains are found in the sample E-13 along with the early stage mosaic structure of vitrinite. Characteristic pores and slits are observed in vitrinite indicating rapid devolatilization.
- Secondary calcite is commonly present in the heat affected samples as infillings into the coal as epigenetic mineral from hydrothermal alteration of the igneous rock (Kisch and Taylor, 1966; Ward et al., 1989; Ward, 2002; Querol et al., 1997; Finkelman et al., 1998).
- The palynomorphs recovered from sample E-13 at 984.95 m depth were opaque reflecting a charred or burnt effect due to the sudden supply of heat which rendered them indistinguishable. Whereas the spores, pollen and phytoclasts of the un-altered coal clearly display their internal structure.

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