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GEOLOGICAL AND COMBUSTION PERSPECTIVES OF PAKISTANI COAL FROM SALT RANGE AND TRANS INDUS RANGE

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Abstract

Abundant availability of low rank coals in some developing countries has great potential for socio-economic development. Pakistan is one of the developing countries where a number of initiatives are being taken take to an advanced stage. In this paper a critical study of regional and local geology of Salt Range and Trans Indus Range coals is presented. The Salt Range and Trans Indus Range are located in the Kohat-Potwar geologic province. Permian coal is the oldest coal which is located in the Western Salt Range in limited quantity while the younger coal is of Palaeocene age and it is mined from the Hangu and Patala formations. The Palaeocene coal is available in abundance and is mined in the Eastern and Central parts of the Salt Range and Trans Indus Range.

Also this study presents the thermo chemical analyses of the coal samples collected from thirty coal mines of Salt Range and Trans Indus Range located in Punjab, Pakistan. Ash composition, Ash Fusion Temperatures (AFT) of coal samples along with Proximate - Ultimate Analysis and Calorific Value were analyzed from two different Labs i.e. SGS Pakistan and Changsha University of Science and Technology (CUST), China. The Average AFT of the samples analyzed is greater than 1350^{0}C which reveals that the coal is non- slagging. On average the coal has low slagging Index, medium fouling Index, good combustion characteristic parameters and indices. The coal samples have high ash (14-50%), ultra-high sulphur (3.3 – 11.1%), low moisture (3-10%), high Volatile Matter (VM) 24-41%, low Carbon (23-57%) with low to medium GCV (10.2 - 25.7 MJ/kg).

The data gathered from an extensive campaign is compared with the already published data. The study has provided an in depth knowledge on utilization of coal reserves to meet the projected energy demand in Pakistan as well as in other developing countries.

Key Words: **Coal, Proximate, Ultimate, Ash Fusion, Combustion, FBC, Salt Range, Trans Indus**

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1.0 Introduction

Coal has huge reserves and low prices in comparison to oil and gas. Depletion time of coal reserves is more than 100 years which is approximately three times bigger than oil and gas. Thus coal being clean energy source will become energy substitute for oil and gas in future [1]. Coal share in the world power generation mix is more than 40% [2]. Coal-fired plants continue to be the largest source of electricity generation all over the world although their market share declines a bit due to exploitation of the renewable resources. In Pakistan, power generation policy has shifted the interest from oil and gas to coal based power generation [3]. At present, the share of coal in power generation of Pakistan is less than 1% [4] and could be increased considerably using low grade coals such as sub-bituminous in Salt Range and Trans Indus Range in Punjab & Baluchistan and lignite in Thar and Lakhra (Sindh). Coal based power generation represents an economic solution by using these low grade local coals of Pakistan as well as use of their blends with imported coals which would ensure high performance and compliance with environmental regulations.

One feasible method for small to medium scale power production is Fluidized Bed Combustion (FBC). This technology is flexible enough to utilize low grade and non-compliant quality coal whilst maintaining low emissions of Sulphur Oxides (SO_x) and Nitrogen Oxides (NO_x) [5-8]. In open literature, geological aspects and combustion perspectives of Pakistani coal have not been fully investigated. The regional geologic studies of the coal-bearing areas in Northern Pakistan were conducted under Potwar Regional Framework Assessment Project (PRFAP) and the assessment of coal resources for Pakistan was done under Coal Resources Exploration and Assessment Program (COALREAP), a joint study by US Geological Survey (USGS) and Geological Survey of Pakistan (GSP) [9]. Latest work on regional geology, local geology, coalfield stratigraphy and coal resources of Salt Range and Trans Indus Range has been done by M/S Snowden for Mines and Minerals Department of Punjab Pakistan [10]. M/s Snowden Australia has confirmed 500 million tons coal reserves in Salt Range and Trans Indus Range [11].

Daood et al [12] performed the combustion test of Thar lignite in pilot scale facility and studied the emissions of the coal like NO_x, CO, CO_2 and SO_2 with slagging and fouling analysis of ash samples at different combustion conditions. Zaidi et al [13] studied the coal reactivity and char formation for the five coals collected from Lakhra, Sindh, Sore-Range & Sharigh, Baluchistan, Makarwal, Punjab, Pakistan and Sin Kiang, China. Iqbal et al. [14] investigated four coal samples from Islamkot, Thar parker and studied the effect of particle size on peak & burn out temperatures and increase in VM on removal of inherent mineral. Naveed et al [15] investigated the coal of Eastern Salt Range (Chakwal) and recommended the coal for gasification. However, the work on Salt Range and Trans Indus Range coal is very limited.

This study focuses on the geology, coal field stratigraphy and combustion perspectives of the coal from the Salt Range and Trans Indus Range. It will help engineering community, government and private sector to make decisions for the investment in design, engineering and installation/setup of coal mines and small to medium size coal power plants. It will help to exploit indigenous coal resources of Punjab particularly and Pakistan generally to produce cheap electricity as compared to oil fired power plants and to bridge the gap between demand and supply of electricity for better economic growth.

2.0 Geology

Geological Map showing Pakistan region under study is given in the Fig. 1 .The Salt Range and Trans Indus Range are located in the Kohat-Potwar geologic province which has the Jhelum Fault in the east, the Kurram Fault in the west and the Parachinar-Murree Fault in the north. The south of the Salt Range lies within the Indus geologic province [9].

Regional Geological Structures of the Kohat-Potwar geologic province is given in Fig. 2.

Geologically, Kohat and Potwar are part of active and the youngest Himalayan Orogeny. The mountains of Kohat and Potwar Plateau falls are known as Sub-Himalayas. The Himalayan Orogeny is the outcome of collision between the mighty Eurasian Plate drifting southward with the Indo-Pak drifting northward one. The collision started somewhere in Eocene (about 65 Million Years ago).Both the Plateaus are separated by Indus River [16]. Structurally, both the plateaus are fold and thrust belts. In the north these are bounded by Main Boundary Thrust (MBT) while in the south these are bounded by Main Frontal Thrust (MFT) [17]. Depositional record of the Kohat-Potwar geologic province is found from Late Proterozoic to Holocene.

The Salt Range as rightly said “THE MUSEUM OF GEOLOGY” extending about 250km East-West and about 7-8 km North-South is the most southern part of the Himalayan Orogeny. It is exposed along the Main Frontal Thrust (MFT). The ramp like structure dipping north, verging south on the Indo-Pak Plate seems to be responsible for the Salt Range thrust (a part of MFT). On the east, the Salt Range terminates along the Jhelum Fault and in the West it terminates with the Kalabagh Fault and from there it runs in North-South direction [18].

2.1 Stratigraphy

Coal of Salt Range and Trans Indus Range is found at three different stratigraphic horizons i.e. rocks of Permian age, Hangu and Patal formations of Palaeocene age. The age range of stratigraphic units of the Salt Range is from Precambrian to Quaternary (Fig. 3). Permian coal is the oldest coal which is located in the Western Salt Range and is limited in quantity. Palaeocene coal is younger coal which is extracted from Hangu and Patal formations and is available in abundance. This coal is mined from Eastern and Central Salt Range and Trans Indus Range. The coal seams are generally developed in the middle part of the Patala Formation which is 18-20m thick in this area [10].

2.1.1 Eastern Salt Range

Earliest coal mining in the Eastern Salt Range dates back to the 1880's. Some of the mines are now well developed. The area covered by the Eastern Salt Range coalfields extends from Ara to Nilawahan (Fig. 4. Intense mining activities are confined to Ara and Dandot. The workable coal seam in this area has been referred to as the 'Dandot coal seam' in previous literature. Clay and sand partings split the coal bed into two or more coal seams in some areas, but generally only one coal layer is worked. The situation in this area is very much similar to that of the Central Salt Range. Thin coal seams ranging from 15 to 22 cm are being mined at a few places, whereas a seam of more than 1 m thick is mined at other places. Such places include east of Khewra where a poor quality pyritic coal, greater than 1.2 m thick has been measured. At Dalwal, the coal seam varies from 0.3 to 1.2 m in thickness. Northwards, thin coal seams, ranging from 15 to 22 cm are also being mined at many places. Eastwards, in the Dalwal and Nilawahan area, the coal seam is a few centimetres [19].

2.1.2 Central Salt Range

The coal mining in the Central Salt Range was started in the beginning of the 20th Century at Katha collieries. The coal seams are not consistent in thickness ranging from 0.08 to 1.5 m. The absence of the coal in certain areas is attributed both to tectonic causes and non-depositional reasons. Generally, the coal is the thickest in the south and the thinnest in the north of the coalfields. In the western part, siltstone and sandstone form the base of the coal seam while in the eastern part shale and clay stone form the coal floor. Facies change from sand and silt to clay stone is observed in the central part of the coalfield. The roof of the coal seams is mostly shale but sandstone and siltstone are also present in various locations. Frequently, a coal seam is inter bedded with sand, silt and shale bands and in some cases these bands are significantly developed to the detriment of the coal seams [19].

2.1.3 Western Salt Range

Permian coal is found at Buri Khel, (Lat 32° 41'N, Long 71° 38' E) in the Western Salt Range, at the top of Tobra Formation. The Permian rocks of other parts of Salt Range are devoid of coal, although in some cases coal streaks are found in the upper part of Tobra formation and Warcha Sandstone.The maximum workable coal seam in this area is 162 cm thick and the average thickness of the coal in Buri Khel area, is 62 cm. The roof and floor of the coal seam is sandstone, which laterally changes into a claystone facies [19].

2.1.4 Trans Indus (Surghar) Range

The coalfields of the Trans Indus Range are confined to Makerwal and its surrounding vicinity. Makerwal coal is found in the Hangu Formation and is mined only from one bed. Danilchik and Shah (1987), made detailed investigations in this area and reported the thickness of the coal bed ranges from less than 1 metre to 3 metres [20].

3.0 Experimental Work

The coal samples were collected from 30 different coal mines of Salt Range and Trans Indus Range for quality analysis including coal quality testing and combustion characteristics of the coal. Detail of samples with the names of the mines and the areas/districts is given in Table1.

3.1 Coal Quality Testing

Following coal quality testing for thirty coal samples was conducted from laboratories of SGS Pakistan and Changsha University of Science & Technology (CUST) China.

I. Proximate Analysis (Moisture, Volatile Matter (VM), Ash, Fixed Carbon (FC)
II. Calorific Value
III. Ultimate Analysis (Carbon, Hydrogen, Sulfur, Nitrogen, Oxygen)
IV. Ash Composition
V. Ash Fusion Temperature

3.1.1 Testing Methodology

SGS used ASTM standards while CUST used GB standards for their analysis.

SGS used furnace (make: carbolite, model AAF12/18 range: upto 1200 ^{o}C) and oven (make: Memmet) for Proximate Analysis, LECO bomb calorimeter for GCV and CHNS analyzer for Ultimate Analysis. Global industry standards were used for ash fusion and ash composition analysis.

CUST used TGA-2000 for Proximate Analysis (make: NAVAS Instrument USA), Infra red moisture balance (model: AD-4712 A&D Tech Japan), Calorimeter (model: SDACM 4000, manufacturer : Hunan Sundy Industrial Co. Ltd Chian), For Ultimate Analysis, Elementar (model: *vario macro manufacturer:* Elementar Analyse n systeme GmbH, donaustraße 7, D-63452 Hanau Germany), For Ash Composition, Silicate's Chemical Component Analyzer, (model: *GKF-VI, m*ake: Hunan Huafeng, Equip. Manufact. Co. Ltd. China) and Ash Fusion Tester, (Model:*SDAF2000 d,* Make: Hunan Sundy Industrial Co. Ltd. China) for ash fusion.

3.2 Combustion characteristics analysis of coal

Simultaneous Thermal Analysis (STA) Instrument NETZSCH STA 449F3 and Ignition Tester (Rui Hai) were used for Combustion characteristics analysis i.e. volatile initial separating temperature, ignition temperature, complete burning temperature, complete burning time, combustibility index, stable firing index, complete combustion index, Integration combustion. These characteristics have been evaluated while following conditions were maintained during the tests.

i. Temperature Range: RT to 1150℃;
ii. Heating Rate: 20℃/min;
iii. Atmospheres: Simulated air atmospheres
iv. Nitrogen Flow: 20ml/min and Pressure: 0.05Mpa;
v. Oxygen Flow: 6ml/min and Pressure: 0.03Mpa;
vi. Coal Sample Weight: 10±1mg;
vii. Coal Sample Size: $< 74\ \mu m$

4.0 Results and Discussion

Testing of Salt Range and Trans Indus Range coal was carried out to investigate the different quality parameters and combustion characteristics of the coal. These results would be helpful to check the suitability of the coal for combustion in steam and power generation plants. This testing is divided into two parts i.e. coal quality testing and combustion characteristics of the coal.

4.1 Coal Quality Testing

It includes Proximate Analysis, Ultimate Analysis, Calorific Value, Ash Fusion Temperature and Ash Composition Analysis.

4.1.1 Proximate Analysis

Proximate Analysis determines the Fixed Carbon (FC), Volatile Matter (VM), moisture and ash percentages in the coal. The amounts of F.C and VM directly contribute to the heating value of coal. Fixed Carbon acts as a main heat generator during burning. High VM content indicates easy ignition of fuel. The ash content is important in the design of the furnace grate, combustion volume, pollution control equipment and ash handling systems of the furnace. Fig. 5 gives the comparison of average results of Proximate Analysis and Calorific Values of the thirty coal samples. There is no major difference in the results of two Labs. However, the results of CUST for Proximate Analysis are more conservative as compared to SGS; therefore, they have been considered for further discussion.

4.1.2 Ultimate Analysis

Ultimate Analysis has great importance in design, performance analysis and combustion control of a coal fired combustion system. The results are useful in determining the quantity of air required for combustion and the volume & composition of the combustion gases. This information is also used for the calculation of flame temperature and flue duct design. Gaseous emissions like SO_x, NO_x, CO and CO_2 can be calculated in the flue gas. $DeSO_x$ and $DeNO_x$ systems are designed on the basis of these results. Fig. 6 gives the comparison of average results of Ultimate Analysis of thirty coal samples from SGS and CUST. There is no big difference in the values of carbon, hydrogen and sulfur as investigated from SGS and CUST but there is great disagreement in the results of nitrogen from the two labs (i.e. CUST: average value > 4% and SGS: average value < 1%). CHNS analysis of the coal has been repeated from the lab of University of Leeds, Leeds, UK and the results of nitrogen are in the range of 1.07% to 1.33% which is close to the SGS results. Therefore for Ultimate Analysis, SGS results have been taken as a reference for further discussion.

4.1.3 Ash Fusion Temperature

This analysis is normally used to assess the coal quality for effective utilization, ash fusibility and its melting behavior during combustion. It could be used as a guide for coal blending, optimizing the use of coal resources and operational parameters of coal fired power plants. It helps to predict the true combustion conditions and suitability of coal for the combustion [21]. Fig. 7 shows the comparison of average results of Ash Fusion Temperatures of 30 coal samples conducted through SGS and CUST.

4.1.4 Ash Composition

Ash content of coal represents the left over mineral matter after the carbon, oxygen, sulfur and water are driven off during combustion. Main purpose of this analysis is to calculate fouling and slagging indices, estimate of slag viscosity against temperature, modeling environmental impact of the ash, reference for ash utilization and estimation of corrosion in the boiler against K_2O, NaO, CaO_2 in ash [22, 23]. Fig. 8 shows the comparison of average results of important constituents of Ash (i.e. Al_2O_3, SiO_2, Fe_2O_3) of 30 coal samples conducted through SGS and CUST.

4.2 Combustion characteristics of coal

The coal combustion consists of de-volatilization of the coal and the heterogeneous combustion of the char. The ignition rate is important combustion characteristics of the coal. Evolution and ignition of volatiles occur simultaneously with higher heating rates however de-volatilization will start before ignition and combustion with low heating rates [24,25].

Mean values of important combustion parameters are given in Table 2. Table 3 shows the results of ignition temperatures and combustion characteristics indices of thirty coal samples.

4.3 Discussion and Recommendation

Certain coal characteristics have great effect on the combustion and emissions of the coal. Comparison of these characteristics of the investigated coal of Salt Range and Trans Indus Range with other local coals (i.e. from Baluchistan and Sindh) & imported coal i.e. high calorie thermal coal (PINANG 6150) of Indonesia [26] is given in the Table 4. In Pakistan, major coal resources and their mining activities are in Sindh, Baluchistan and Punjab. Quality of local coal is low grade i.e. lignite in Thar & Lakhra and subbituminous in Punjab and Baluchistan. Good quality coal is being imported from Indonesia, South Africa, Australia and Afghanistan. Indonesian coal has major share in the import; therefore, it has been taken as representative of the imported coals and compared with local coal in this study.

Maximum moisture content in the coal investigated is 10.4 % against 10% for high calorie thermal sub bituminous coal (PINANG 6150) from Indonesia and 11.5% for Duki coal (Baluchistan). Maximum moisture in Degari coal is 18.9% while the moisture contents in the Lakhra and Thar coal are 38.1% and 55.5% respectively which are 4 to 5 times more than the investigated coal. Therefore moisture in the investigated coal is almost equal to high calorie thermal imported (Indonesian) coal and less than good quality coal of Baluchistan and far less than Lakra and Thar coals. Higher moisture in the coal causes spontaneous combustion [27] during transportation and storage of the coal. Moisture also plays an important role in combustion of the coal. Higher moisture in coal decreases the furnace temperature and eventually reduces the boiler efficiency. Higher moisture coals also have big difference between GCV and NCV. Therefore, low moisture coal is considered most suitable for combustion [28-30].

Volatile Matter (VM) in the coal ranges from 24.2 % to 40.5% with mean value of 32.6% on air dry basis (adb) which is in line with the values of VM of Degari (20.7% - 37.5%), Lakhra (18.3% - 38.6%) and Thar (23.1% - 36.5%). However, values of VM for Duki and Indonesian coal are 32% - 50% and 38% - 45% which have good thermal qualities. Average value of VM of the investigated coal is 33.6% on dry basis and 49.69% on dry ash free (daf) basis. It falls under the category of high volatile sub bituminous coal. Normally high VM coal gets easily spontaneous combustion. Extra care is required during the transportation and storage of such coal. It also may cause slagging in the furnace which disturbs the air flow inside the bed.

Ash contents in the investigated coal range from 14.2 % to 50.3% with mean value of 33.4% (adb) which is almost in line with the ash contents of Duki (5% - 38%) and Lakhra (4.3% - 49%), however, ash contents of Degari (4.9% - 17.2%) and Thar (3.9% -11.5%) are quite less and comparable to Indonesian coal (14% max). Average value of ash in the investigated coal on dry basis is 34.6% which is higher than good quality coal. Higher ash content in the coal reduces the efficiency of the boiler. Ash also causes serious erosion to the boiler parts and it is a big challenge to keep the boiler in long term continuous operation with high ash coal. However, heat from bottom ash could be utilized by means of different waste heat recovery technologies to improve heat rate of the plant.

Fixed carbon in the investigated coal ranges from 22.2% to 42.2 % with mean value of 31% which is less than Duki (28% - 42%), Degari (41% - 50.8%) and Indonesian coal (40.2%) and is greater than Lakhra (9.8% - 38.2%) and Thar (14.2% - 34%) coal. This coal has low carbon and if the carbon content in the coal is low, its GCV will be low and ash will be high and vice versa in case of high carbon value.

For complete combustion, carbon needs sufficient time and temperature having good mixture with air. If carbon residence time is not sufficient, it could not be combusted completely. Coal particle size should be according to design and in the required distribution ratio. If the coal particle size is too small, it may blow off with fluidizing velocity and causes an increase of the carbon in fly ash. If the size of coal particles is too large it might not be combusted perfectly even after circulation of multiple times in FBC boiler and it may increase the carbon in bottom ash. Such cases will increase the Non-Complete Combustion Loss [5].

Sulfur in the investigated coal ranges from 3.3 % to 11.1% with mean value of 7.1% (adb) which is greater than the sulfur contents in the coals from Duki (4% - 6%), Degari (0.6% – 5.5%), Indonesia (1 % max) & Thar (0.4% - 2.9%) and less than the sulfur in Lakhra coal (1.2% - 14.8%). Sulfur is a combustible substance and can be completely converted to SO_2. Due to higher SO_2 concentration, the moisture contents in the flue gas will condense and combine with SO_2 to form sulfuric acid. To avoid the acid formation in the flue gas duct, it becomes necessary to increase the exit temperature of flue gas which causes an increase in flue gas loss. If SO_2 is emitted to the atmosphere, it will combine with the moisture in the clouds, and causes acid rain which may destroy the structures and crop land. For elimination of SO_2 in flue gases, limestone is mixed with the coal and Ca/S ratio could be 1 - 5 [31] in FBC boiler depending upon limestone quality, particle size, the quality of solid mixing, combustion temperature, degree of fly ash recirculation in case of CFBC and schematic of coal and limestone feeding points [32]. To get the same desulfurization efficiency, the Ca/S ratio should be higher than 4 for grate boiler and higher than 6 for Pulverized Fuel Boiler [33]. Addition of more limestone for higher sulfur in coal may form CaS that is one kind of catalyst which facilitates nitrogen to be converted to NO_x. Hence, FBC boiler burning high sulfur coal, with in-furnace desulfurization may cause an increase in NO_x emission. Therefore, it is necessary to optimize the combustion with desulfurization to avoid increase in NO_x over the emission limits [34].

Normally, nitrogen is found in the organic form inside the coal and it is converted to NO_x during coal combustion. NO_x is harmful mixture gas of NO and NO_2. This is the most common case in FBC boiler. Other source of the Nitrogen is from air which is required for coal combustion. The conversion of nitrogen via the thermal NO_x formation mechanism is relatively less significant especially in case of FBC Boiler (operating temperatures ~ 950^{o}C). Therefore, for high nitrogen coal fuel, FBC is the best choice [35].

GCV of the investigated coal ranges from 16.0 to 36.6 MJ/Kg with mean value of 26.3 MJ/Kg on DAF basis. This value is less than the heating values of the coal from Indonesia (35.2 MJ/Kg), comparable up to some extent of the coal from Duki (23.6 - 32.9 MJ/Kg) and Degari (26.2 – 32.12 MJ/Kg) and greater than the coals of Lakhra (12.9 - 21.3 MJ/Kg) and Thar (14.5 - 25.7 MJ/Kg).

According to ASTM standard, quality of the coal of Salt Range and Trans Indus Range is sub-bituminous A on the basis of average values of GCV (26.3), moisture (7.8%), ash (33.4%), volatile matter (32.6%) and sulfur (7.1%) [Table 4].

As evident from Fig. 7, average Ash Fusion Temperatures of the coal in oxidizing environment are 1359 ^{0}C (IDT) , 1372 ^{0}C (ST),1388 ^{0}C (HT) and 1405 ^{0}C (FT), which are greater than 1350 ^{0}C showing that the coal is non- slagging [36]. Similarly the average fouling index of the coal is 2.13 which lies near the bottom line of the range 0.6 - 40. Therefore, this coal is not causing serious fouling problems [37].

Table 3 shows the ignition temperatures and combustion characteristics indices like ignition characteristics index (F_z), flammability index (C) and stable firing index (M) of 30 coals. Ignition temperatures of all the coals are less than 400 ^{0}C (355 - 392^{0}C) indicating that the coal is easy for ignition. Value of F_Z is 1.5 – 2.0 for the coals 1, 2 & 6 and greater than 2.0 for the remaining coals which shows that all the coals have very good ignition characteristics. Similarly value of C of all the 30 coals is greater than 2.3 (2.6 - 3.1) which indicates that these coals have excellent flammability characteristics. The value of M of all the coals is greater than 3.3 (3.5 to 4.1) which ensures that these coals have ideal characteristics of stable firing [38].

Thus the average coal of Salt Range and Trans Indus Range has low slagging index, medium to high fouling index, good combustion characteristics parameters and excellent combustion characteristics indices.

In view of all the above mentioned quality parameters, the coal of Salt Range and Trans Indus Range is found suitable for combustion in coal fired power plants for power generation and FBC Technology could be the best choice for combustion of this coal.

Three different scenarios have been discussed regarding quality of coal, combustion prospects and sites for blending facilities of the coals from different mines/areas.

Scenario-I: Use of representative (average) coal of Salt Range and Trans Indus Range for combustion

Average coal of Salt Range and Trans Indus range has low moisture, high ash, ultra high sulfur, high VM and low GCV. Table 5 shows the recommended blends to get the average coal. To burn such kind of coal, FBC technology could be one of the best choices. Values of moisture, VM and GCV in the coal seem suitable for combustion but sulfur and ash are the most challenging problems of this coal. Average value of sulfur is 7.1% and the following two methods are applied for desulfurization of coal to reduce SO_2 in gaseous emissions.

a) In furnace desulfurization: Normally limestone is fed into the furnace with coal for desulfurization during combustion. Salt Range has huge resource of good quality limestone which is being used by many cement factories operating in this area. It is available on the cheaper rates and can be used with coal for desulfurization purpose. Ca/S ratio can be set from 1 to 5 depending upon quality and particle size of limestone to achieve maximum desulfurization efficiency [39]. Only desulfurization during combustion process cannot achieve the higher environmental protection requirements for such high sulfur coal. Therefore post combustion desulfurization is also required.

b) Post-combustion desulfurization: It is also known as Flue Gas Desulfurization (FGD) [40,41]. There are two types of Flue Gas Desulfurization Process i.e. Wet Flue Gas Desulfurization Process (WFGD) *[42]* and Dry Flue Gas Desulfurization (DFGD). Both technologies have their own merits and demerits. Any technology can be adopted according to requirement and priority of the end user.

Using above mentioned desulfurization technologies, SO_2 limits in gaseous emissions can be achieved up to 200 mg/NM^3 which meets European Standard of gaseous emission from coal fired power plants.

Average ash content in the investigated coal is 33.4% which is higher than ash content of any good quality coal. So combustion of the coal having high ash needs huge amount of water to cool down the bottom ash from bed. However, heat from the bottom ash can be utilized through different waste heat recovery technologies to increase the efficiency of the steam generation and its consumption processes. Burnt ash is a huge byproduct of coal fired power plant burning high ash coal and it must be properly utilized to improve the economics of the plant.

Following are some possible uses of burnt ash of coal fired power plant:

I. The resultant ash could be utilized for manufacturing of ash bricks of different sizes, density and shapes according to market requirement. These ash bricks might be cheaper than the normal clay bricks in Pakistan. Complete feasibility study could be done for installation of ash bricks manufacturing plant on the basis of burnt ash from a coal fired power plant.
II. The byproduct ash could be sold to cement plants which are operating in the vicinity of Salt Range and are very close to the coal fired power plants if they are installed on mine mouth. Therefore, transportation of byproduct ash to cement plants will be convenient and cheaper. This could be viable option for both buyer and seller.
III. The burnt ash could also be subjected for the use in the construction and maintenance of roads as a binding and foundation material; especially in such areas where soil quality is poor. This is the case for Salt Range area because of land sliding and presence of salt in the soil.
IV. Having strong binding characteristics, the burnt ash may also be used in the construction of Dams to increase their life and avoid the possible sliding.
V. The bottom ash sometimes could be also used for leveling of the land.

Average coal being representative coal of Salt Range and Trans Indus Range could be used as design coal for coal fired power plant. All the performance guarantees regarding heat rates and thermal efficiencies of the plant should be based on this coal.

Scenario-II: Use of different blends of local coal and imported coal for combustion (based on quality)

Table 6 shows the different blends of Salt Range and Trans Indus Range coal on the basis of GCV, sulfur and ash. Blends 1, 2 & 3 have better quality than average coal of Salt Range and Trans Indus Range and could be used directly for combustion using FBC technology.

Quality of the coal blends 4 and 5 is poor than that of average coal and they could be mixed with good quality imported coal (i.e. Indonesian coal) to improve their quality.

Table 7 shows five different mixing schemes of imported coal (from 10% to 50%) with low quality local coals (blends 4 & 5) to improve their quality and make them suitable for combustion in coal fired power generation systems.

For blend 4 of local coal, any mixing scheme from (10% - 50%) could be used depending upon the required quality of the coal. Mixing of 10% imported coal make its quality equal to average coal of Salt Range and 50% mixing makes it equal to or even better than the best coal of Salt Range. For blend 5, mixing of 30% imported coal is required to get the coal quality comparable of the average coal of Salt Range. Further increase in percentage of imported coal may be made according the required quality with due consideration of economic feasibility.

Scenario-III: Use of different blends of local coal for combustion (on geographical basis)

Keeping in view the discussion in Scenario-I and Scenario-II, it would be worthwhile to get the blends of coal on geographical basis. It is more convenient, economical and feasible to use coal blends on geographical basis.

Table 8 shows the five blends of local coals and their characteristics on geographical basis. Blends 1 and 2 have low GCV, high ash and high sulfur which shows that the coals of Eastern Salt Range (i.e. Chakwal) and Central Salt Range (PEL/Padhrar) have high sulfur as compared to the average coal. GCVs of blends 3 & 4 of Central Salt Range (Chamble Zone) and blend 5 of Trans Indus Range are higher and their sulfur & ash are lower than the average coal. Thus the coal quality of this area is better than the average coal and can be used directly for combustion in coal fired power plant.

Coal quality of blends 1 & 2 is lower than the average coal of Salt Range and it could be mixed with imported coal to improve its quality for better combustion results.

4.4 Conclusion

A brief study of regional and local geology of Salt Range and Trans Indus Range coal is presented in this paper. The Salt Ranges and Trans Indus Ranges are located in the Kohat-Potwar geologic province which has the Jhelum fault in the east, the Kurram fault in the west and the Parachinar-Murree fault in the north. The south of the Salt Range lies within the Indus geologic province. Geologically, Kohat and Potwar are part of active and the youngest Himalayan Orogeny.

Earliest coal mining in the Eastern Salt Range dates back to the 1880's. Some of the mines are now well developed. Thin coal seams ranging from 15 to 22 cm are being mined at a few places, whereas a seam of more than 1 m thick is mined at other places. The coal mining in the Central Salt Range was started in the beginning of the 20^{th} century at Katha collieries. The coal seams are not consistent in thickness ranging from 0.08 m to 1.5 m. In the Western Salt Range, the maximum workable coal seam is 162 cm thick and the average thickness of the coal in Buri Khel area is 62 cm. Makerwal coal is found in the Hangu Formation and is mined only from one bed and the thickness of the coal bed ranges from less than 1 to 3 meter. Plow technology could be the best technique for mining of thin coal seams of Salt Range and Trans Indus Range.

A comprehensive investigation is done on the coal samples collected from Salt Range and Trans Indus Range of Punjab, Pakistan. Comparative analysis of coal quality of the coal has been carried out with local as well as imported coals. The results confirm that the coal has high sulphur (3.3 – 11.1 %), high ash (14.2 % - 50.3%) and low GCV (10.2 – 25.7 MJ/Kg) and falls in the category of sub-bituminous coal. Ash Fusion Temperatures (>1350^{o}C) and Ash Composition indicate that the coal has non slagging behavior and no fouling problem. Three different scenarios have been discussed in view of the average coal, blends of the coal on the basis of different quality parameters and the coal blends on the geographical basis. These scenarios focused on the important combustion parameters and characteristics of the coal, recommendation of different blends of the local as well as imported coal to improve the quality and competitive combustion technology for burning of the coal. It is concluded that the use of low grade coal for power generation in Pakistan could solve the serious shortfall of electricity in the country.

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Table 1

Detail of Coal Samples collected from Salt Range and Trans Indus Range

Sample	Mine	Area/District	Sample	Mine	Area / District
1	Hashim Mine,	Munara,Chakwal	16	Mine No.5	Kalial, Khushab
2	Mine“C”	Munara,Chakwal	17	Ehsaan Mine	Arrarah Khushab
3	Habib Ullah Mine	Munara,Chakwal	18	Tariq Mine	Arrarah Khushab
4	Shaft“A”	Padhrar,Khushab	19	Zia Mine	Kalial, Khushab
5	Sangha Mine	Padhrar,Khushab	20	Rehman Mine	Kalial, Khushab
6	Mine No.5	Padhrar,Khushab	21	Mine No.7	Kalar Kahar Chakwal
7	Mine No.2	Khatta, Khushab	22	Abubakar Mine	Kattas Raaj, Chakwal
8	Amina Mine	Nalli Khushab	23	PC-1 Mine	Gula Khall Mianwali
9	Old Bashir Mine	Kalial, Khushab	24	Majid Latif Mine	Gula Khall Mianwali
10	Piari Mine	Kalial, Khushab	25	Tarkia Mine	Gula Khall Mianwali
11	New Bashir Mine	Kalial, Khushab	26	Abaid Ullah Mine	Makarwal, Mianwali
12	Sulman Mine	Kalial, Khushab	27	Maadin e Haq Mine	Makarwal, Mianwali
13	Mine No.3	Kalial, Khushab	28	Khatkiara Section A	Makarwal, Mianwali
14	Mine No.1	Kalial, Khushab	29	Khatkiara Section B	Makarwal, Mianwali
15	Mine No.4	Kalial, Khushab	30	Khatkiara Section C	Makarwal, Mianwali

Table 2

Combustion Parameters from CUST China (Range, Mean, Std. Deviation & Variance)

	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
T_s	59.0	221.0	280.0	256.4	13.2	173.8
T_h	95.0	547.0	642.0	603.2	22.9	524.4
t_{rj}	5.0	8.8	13.8	11.6	1.3	1.8
w_{max}	0.1	0.6	0.7	0.6	0.0	0.0
T_{max}	51.0	471.0	522.0	484.9	9.6	92.3
w_{mean}	0.1	0.5	0.6	0.5	0.0	0.0
ΔT_h	95.0	45.0	140.0	92.3	24.7	609.3
ΔT	117.0	141.0	258.0	204.2	29.8	885.7

where

T_s = the volatile initial separating temperature，℃； T_h = the complete burning temperature，℃；

t_{rj} = the complete burning time, min； w_{max} = the max combustion rate $[(dw/d\tau)_{max}]$，mg/mi

w_{mean} = the average burning rate $[(dw/d\tau)_{mean}]$，mg/min； T_{max} = the temperature of maximum combustion rate，℃；

T_h = the temperature difference of DTG's half peak width，℃； ΔT = the temperature difference of DTG's total peak width，℃.

Table 3

Ignition Temperatures and Combustion Characteristics Indices of 30 coal samples

Sample	Ti (℃)	F_Z	C	M	Sample	Ti (℃)	F_Z	C	M
1	384	1.913	2.702	3.668	16	366	3.019	2.838	3.812
2	392	1.851	2.675	3.638	17	356	4.607	2.666	3.629
3	381	2.066	2.570	3.526	18	355	3.519	2.826	3.800
4	372	3.724	2.619	3.578	19	366	6.337	2.796	3.768
5	380	3.153	2.590	3.548	20	359	5.818	3.019	4.006
6	371	1.681	2.817	3.791	21	358	3.323	2.751	3.720
7	356	5.660	2.845	3.820	22	363	5.855	2.868	3.845
8	375	2.319	2.561	3.517	23	371	6.143	3.043	4.031
9	372	5.437	2.743	3.711	24	369	5.029	3.037	4.025
10	361	3.920	2.901	3.880	25	380	3.340	3.041	4.029

11	365	5.498	2.635	3.596	26	368	8.016	2.720	3.687
12	369	2.262	2.814	3.787	27	376	3.274	3.080	4.071
13	361	5.579	2.663	3.626	28	383	5.086	3.123	4.116
14	370	2.148	2.726	3.693	29	371	5.185	3.105	4.097
15	380	3.966	2.935	3.916	30	368	3.422	2.951	3.933

Ti = Ignition Temp, Fz : Ignition Characteristics Index, C: Flammability Index, M = Stable Firing Index

Table 4

Comparison of coal characteristics of Salt Range and Trans Indus Range coal with local and imported coals

Coal Charact-erisics	Sample Coal			Imported Coal			Local Coal							
	Punjab			Indonesia			Baluchistan				Sindh			
	Salt Range and Trans Indus Range			PINANG 6150			Duki		Degari		Lakhra		Thar	
	Min	Max	Mean	Min	Max	Mean	Min	Max	Min	Max	Min	Max	Min	Max
Total Moisture (%) (ADB)	3.2	10.4	7.8	--	10.0	9.0	3.5	11.5	3.9	18.9	9.7	38.1	29.6	55.5
Volatile Matter % (ADB)	24.2	40.5	32.6	38	45	42.5	32	50	20.7	37.5	18.3	38.6	23.1	36.5
Ash % (ADB)	14.2	50.3	33.4	--	14	14.0	5.0	38	4.9	17.2	4.3	49	3.9	11.5
Fixed Carbon % (ADB)	22.2	42.2	31.0	--	---	40.2	28	42	41	50.8	9.8	38.2	14.2	34
Sulfur % (ARB)	3.3	11.1	7.1	--	1.0	0.7	4.0	6.0	0.6	5.5	1.2	14.8	0.4	2.9
GCV (DAF) (MJ/kg)	16.0	36.6	26.3	34.4	35.5	35.2	23.6	32.9	26.2	32.3	12.9	21.3	14.5	25.7

ADB: Air Dry Basis
ARB: As Received Basis
DAF: Dry Ash Free

Table 5

Recommended blends to get average coal of Salt Range and Trans Indus Range

Blends	Coals						GCV (MJ/kg)	Ash%	Sulfur%	TM%	VM %	F.C %
1	2	6	15	19	22	26	19.2	32.0	7.0	8.8	33.0	31.9
2	7	11	12	13	14	27	18.8	33.4	7.3	8.0	32.1	31.7
3	4	8	9	16	18	20	18.9	33.4	7.0	7.5	31.8	31.7
4	1	3	17	23	29	30	18.6	34.5	7.3	7.8	32.4	30.2
5	5	10	21	24	25	28	18.7	34.0	7.1	6.6	33.7	29.5
Average coal of Salt Range/Trans Indus Range							**18.8**	**33.5**	**7.1**	**7.7**	**32.6**	**31.0**

Table 6

Recommended blends of local coal on the basis of GCV, Sulfur and Ash

Blends	Coals						GCV (MJ/kg)	Sulfur %	Ash %
1	11	13	19	21	22	26	22.68	5.55	23.90
2	9	17	18	20	23	29	20.95	6.43	27.97
3	4	10	15	16	24	30	18.98	7.03	33.93
4	3	5	12	25	27	28	16.72	7.77	38.63
5	1	2	6	7	8	14	14.90	8.8	42.75

Table 7

Recommended blends of low quality coal of Salt Range and Imported coal

Blends of local coal	**Quality parameters**	**Imported (100%)**	**Local (100%)**	**Different blends of imported and local coal (%Imp + %local)**				
				(10+ 90)	**(20 + 80)**	**(30+ 70)**	**(40 + 60)**	**(50 + 50)**
Blend 4	GCV (MJ/Kg)	27.5	16.72	17.80	18.88	19.95	21.03	22.11
	Sulfur (%)	14	38.6	36.14	33.68	31.22	28.76	26.30
	Ash (%)	0.7	7.8	7.09	6.38	5.67	4.96	4.25
Blend 5	GCV (MJ/Kg)	27.5	14.9	16.16	17.42	18.68	19.94	21.20
	Sulfur (%)	14	42.8	39.92	37.04	34.16	31.28	28.40
	Ash (%)	0.7	8.8	7.99	7.18	6.37	5.56	4.75

Table 8

Recommended blends of coal on geographical basis

Blends	Mines Areas	Coals								GCV MJ/Kg	Sulfur %	Ash %
1	Eastern Salt Range (Chakwal)	1	2	3	21	22				16.6	6.9	39.8
2	Central Salt Range (PEL/ Padhrar)	4	5	6	7	8				17.0	9.0	37.4
3	Central Salt Range (Chamble Zone 1)	9	10	11	12	13	14			19.4	6.6	32.6
4	Central Salt Range (Chamble Zone 2)	15	16	17	18	19	20			20.0	6.3	30.8
5	Trans Indus Range (Mianwali)	23	24	25	26	27	28	29	30	20.2	7.1	29.6

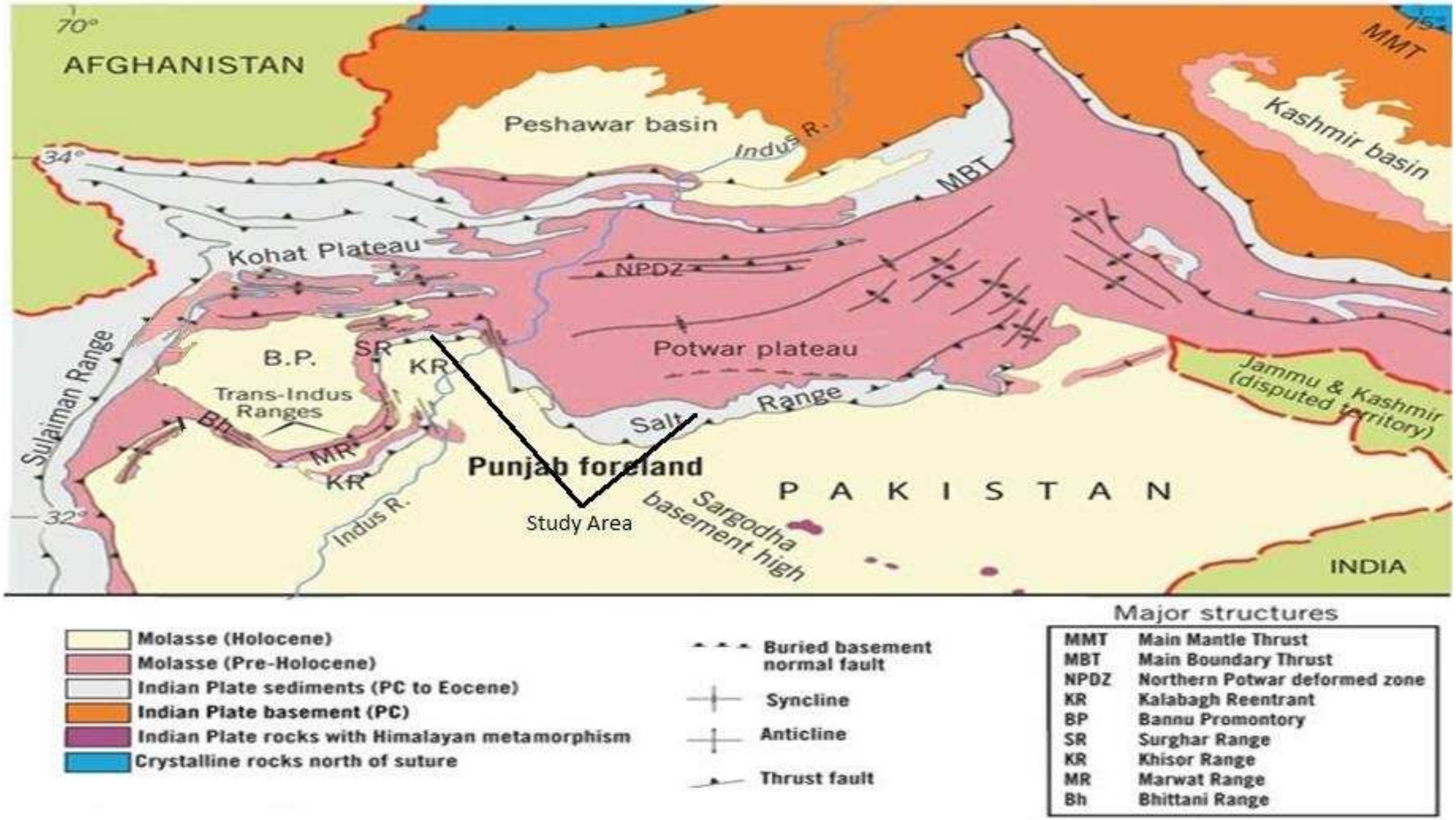

Fig: 1. Salt Range and Trans Indus (Surghar) Range on geological map

(Modified after Kazmi and Rana,1982)

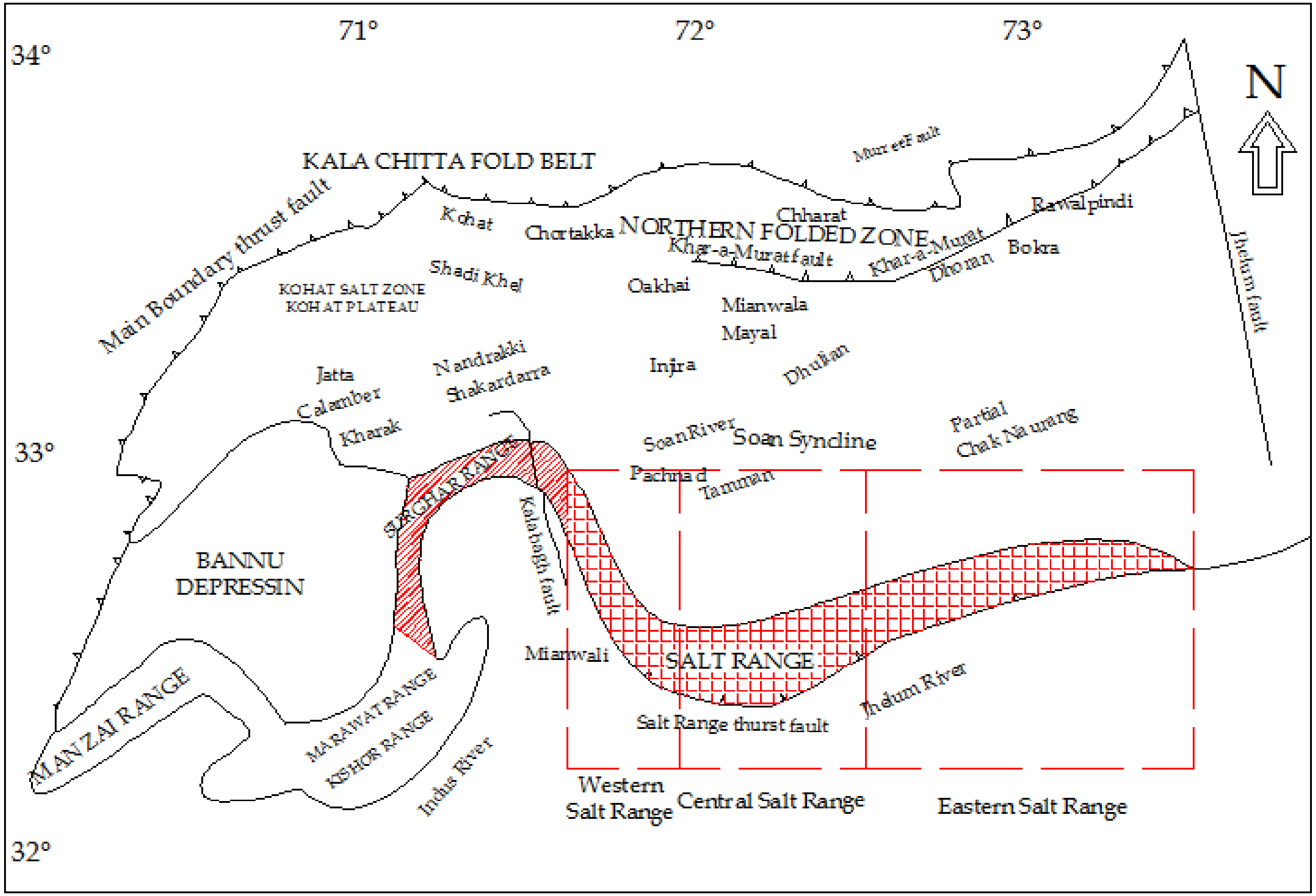

Fig: 2. Regional Geological Structures of the Kohat-Potwar geologic province

(Modified after Wandrey et. al. 2004).

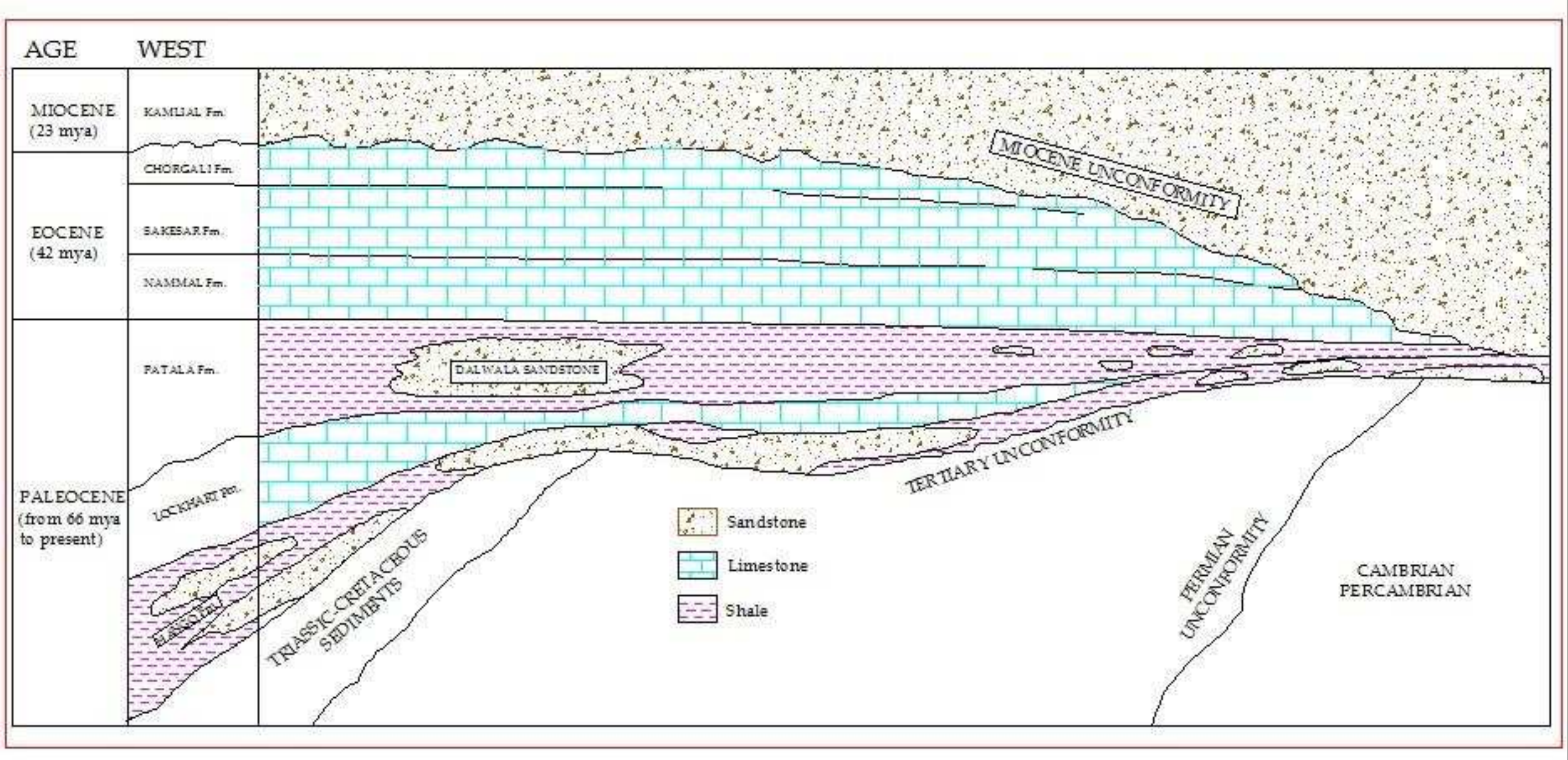

Fig: 3. Generalized east-west cross-section through the entire Salt Range

(Modified after Snowden report, 2012)

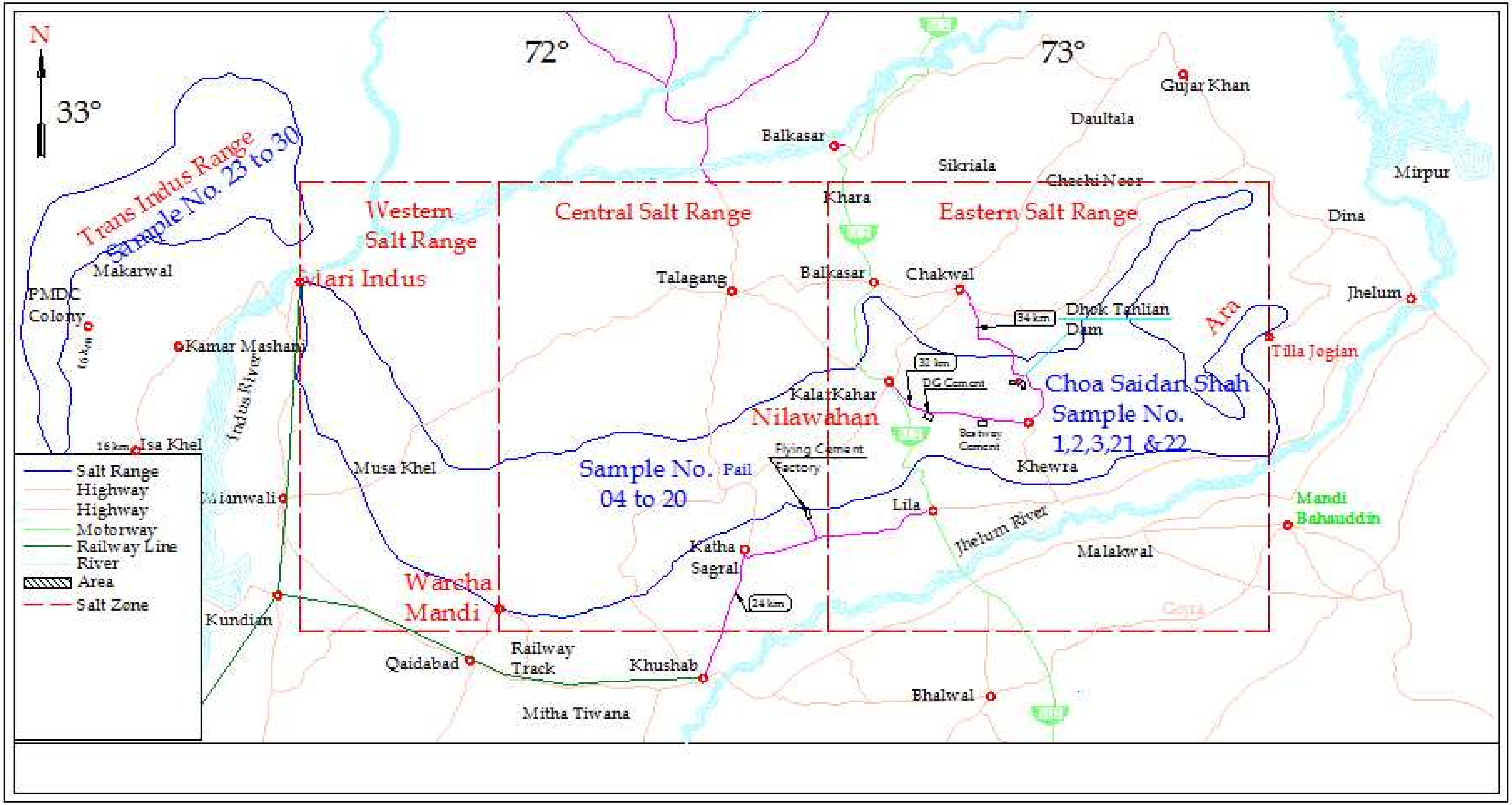

Fig: 4. Location of Salt Range and Trans Indus Range with geographic divisions

(Modified after Warwick and Wardlaw, 2007 and Snowden report, 2012)

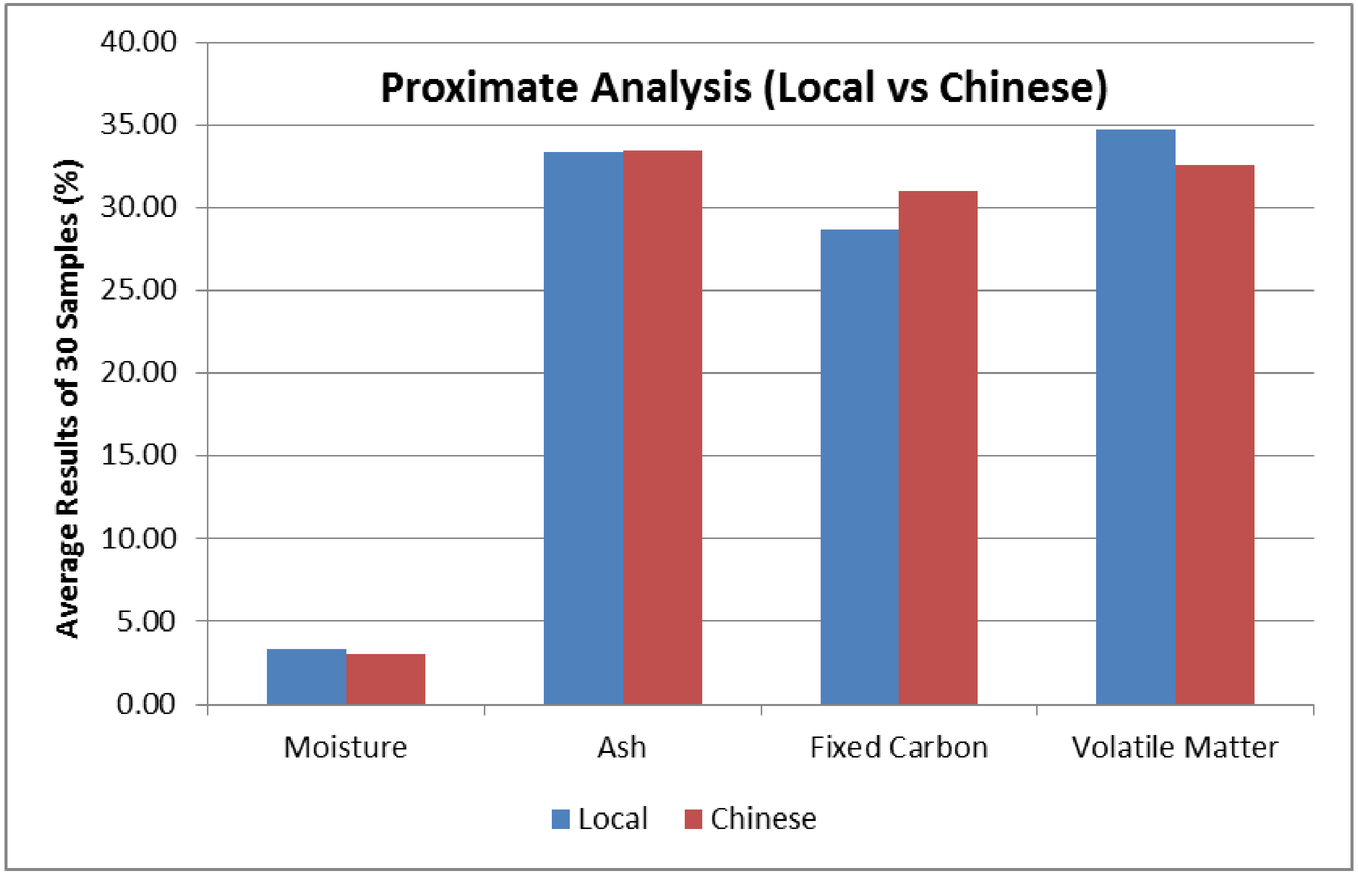

Fig: 5. Comparison of average values of Proximate Analysis for 30 samples

(SGS Vs CUST)

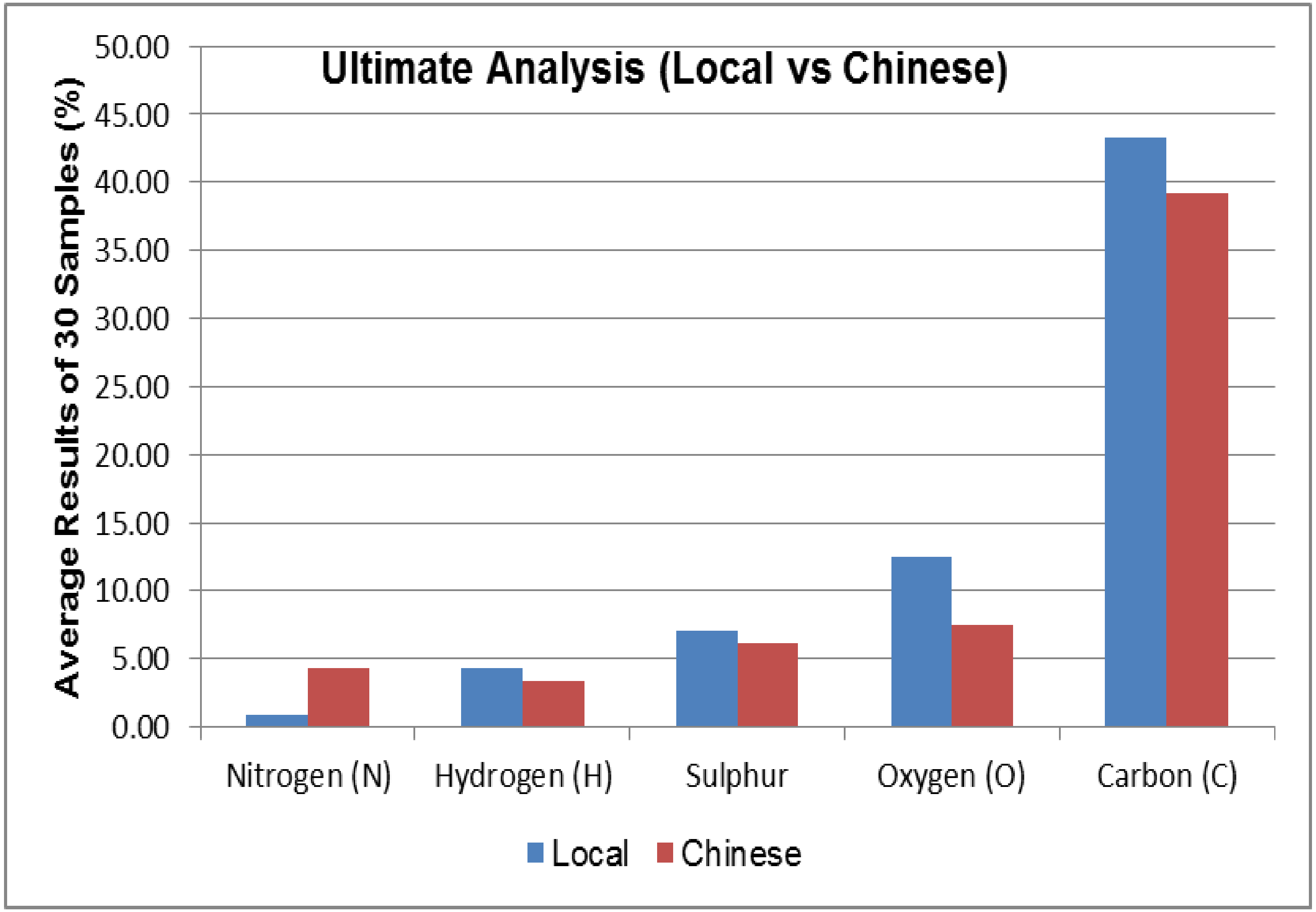

Fig: 6. Comparison of average values of Ultimate Analysis for 30 samples (SGS Vs CUST)

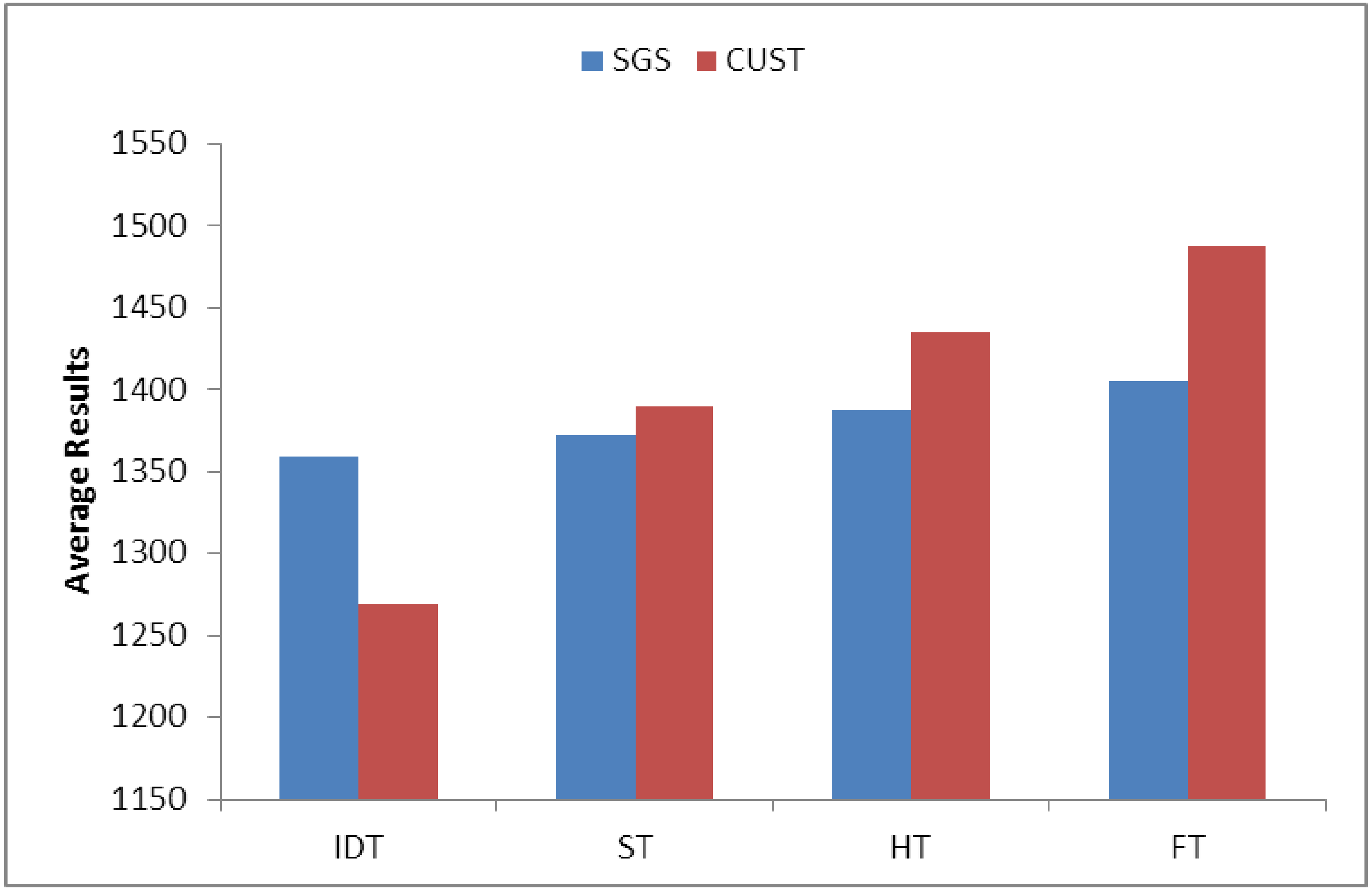

Fig: 7. Comparison of average values of Ash Fusion Temperatures (SGS Vs CUST)

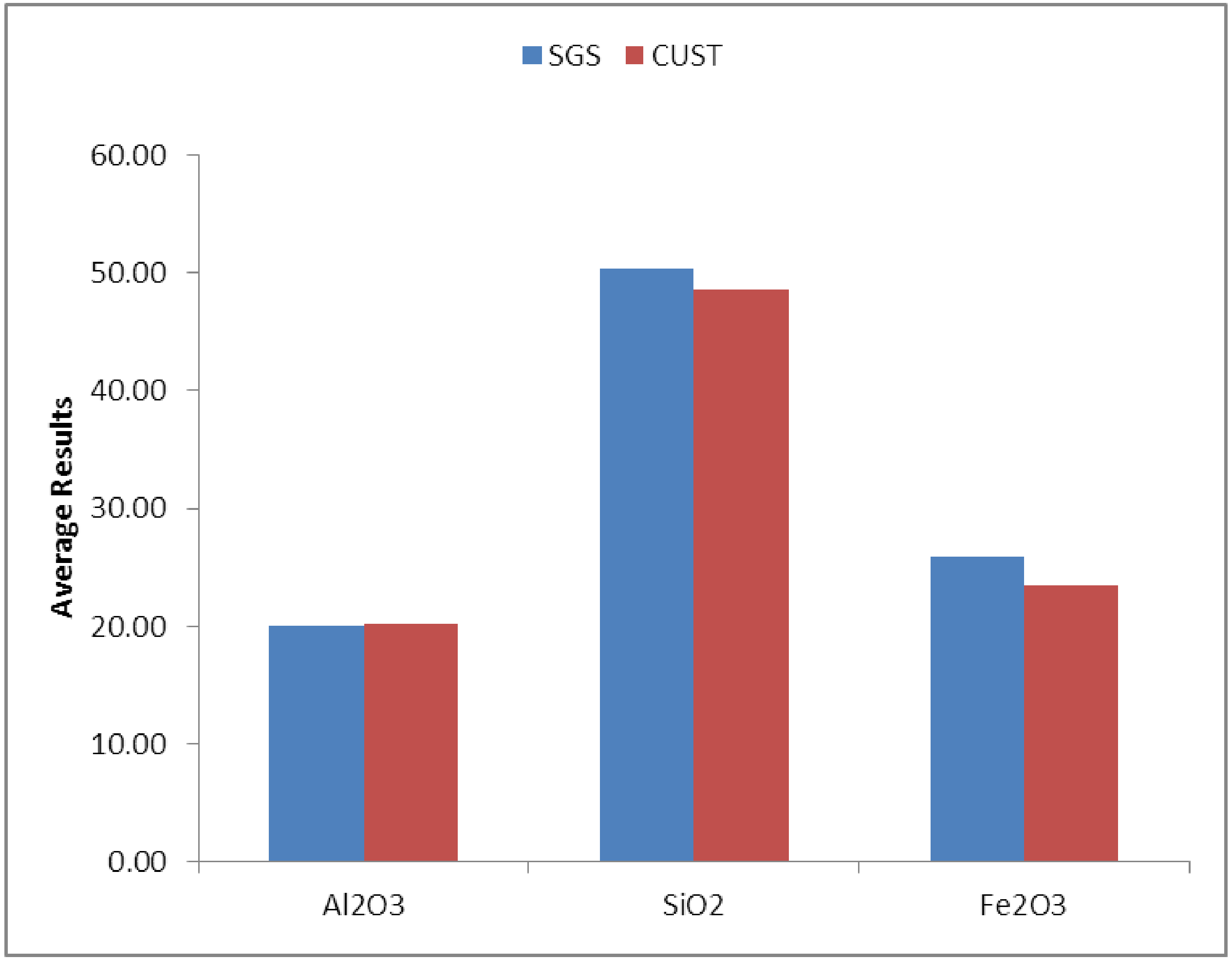

Fig: 8. Comparison of average values of Ash Composition (SGS Vs CUST)