Journal of Sustainable Mining 17 (2018) 111–119

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Journal of Sustainable Mining

journal homepage: www.elsevier.com/locate/jsm

Research paper

Integrated 3D geological modeling of Sonda-Jherruck coal field, Pakistan

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ARTICLE INFO

Keywords:
3D geological modeling
Solid modeling
Coal resource estimation
Fault modeling

ABSTRACT

Despite being one of the largest coal fields in Pakistan, the Sonda-Jherruck coal resource is yet to be exploited. Exploration studies were done between 1981 and 1989 by the Geological Survey of Pakistan (GSP) and the United States Geological Survey (USGS). While much exploratory data is available, computer-aided geological modeling has not been carried out. The resource estimation was carried out using the traditional circular 891 method. The specified distance between observational points remains constant, disregarding continuity in seam thickness that leads to higher uncertainty. Fault modeling and geologic mapping were not performed in preliminary reports. Fault lines based on aerial maps are indicated. This study generated 3D solid seam models and a fault model of the deposit. Coal seams were modeled to produce spatial distribution maps for seam thickness. The overall in-place coal resources of the deposit are estimated to be 4.66 billion tons, however mineable resources are estimated to be 1.59 billion tons. The method of fault detection is based on drill hole data. Dipping was calculated using regular grid data and the unknown points were estimated using the inverse distance weighting squared method. The assessed fault zones were compared with the USGS fault lines and an apparent similarity was observed.

1. Introduction

3D geological modeling is efficient technology for estimating mineral resources and for interpreting and locating surface and subsurface characteristics, both qualitatively and quantitatively. This type of modeling is mainly based on drill hole data, geological maps and survey records of structural information (Wang & Huang, 2012; Wu, Xu, & Zou, 2005).

The Sonda-Jherruck coal field is the second largest coal field in Pakistan, covering an area of approximately 1822 km^2, and is yet unmined. This coal field was discovered by the GSP in 1981, near the small village of Sonda, situated in the Thatta District, Sindh, Pakistan. Fig. 1 shows the geographical location and representation of the exploratory drill hole location and coal field boundary. Between 1981 and 1989 several exploration studies were executed by the Geological Survey of Pakistan (GSP) with assistance from the United States Geological Survey (USGS). The USGS Coal Resource Classification System was used to estimate the coal resources of the study area (Ahmed, Ahmed, Siddiquie, & Khan, 1988; Quadri & Shuaib, 1986; SanFilipo, Khan, & Chandio, 1994; Schweinfurth & Farhat, 1988, p. 36; Schweinfurth, SanFilipo, & Simon, 1985; Schweinfurth, SanFilipo, Landis, Khan, & Shah, 1990; Thomas, Riaz, & Ahmed, 1993).

The Sonda-Jherruck coal field is situated in the Kirthar geologic range of the Lower Indus Basin and the slope platform tectonic zone of Thar (Quadri & Shuaib, 1986). The field is characterized by a north-south trending, lentiform anticline, comprising thick lenses of siltstone and mudstone. The age of the coal field in stratigraphic units ranges from Paleocene to Eocene. The Paleocene (Bara Formation) and Eocene (Laki Formation) sequences are separated by an unconformity (Lakhra Formation).

Most of the identified coal deposits found in the Paleocene Bara Formation and all the exploration activity has been directed almost exclusively towards assessing the coal potential. Less voluminous and discontinuous coal seams are also found in the Paleocene Sohnari Member of the Laki Formation.

The Laki formation is comprised of limestone, clay stone, siltstone and shale. The Sohnari Member consists of lateritic clays, sandstone and gypsiferous shale. The Lakhra formation is comprised of sandstone, limestone, clay stone and siltstone. Sandstone is predominant in the basal layers, while limestone is predominant at the top and alternates with sandstone and clay stone.

Seven major coal containing zones have been found in the area. Most of the coal occurs at three main horizons, which have been named Daduri, Sonda and Jherruck. The most persistent and thickest coal seam

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https://doi.org/10.1016/j.jsm.2018.06.001
Received 19 February 2018; Received in revised form 18 April 2018; Accepted 4 June 2018
Available online 05 June 2018
2300-3960/

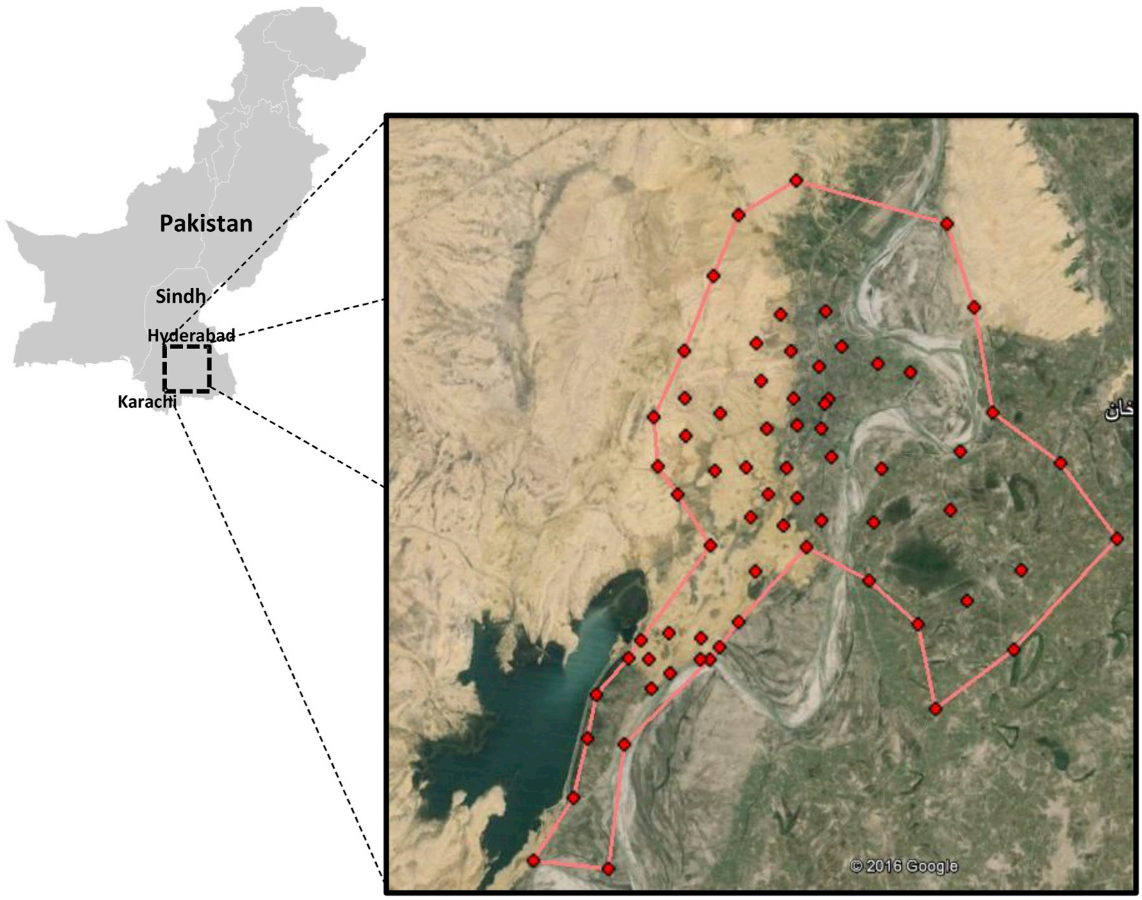

Fig. 1. Location Map of Sonda-Jherruck Coal field, Pakistan (the coal field boundary and drill holes are shown).

(up to 6 m) occurs in the Sonda zone, which lies between the depths of 80–400 m. Four less persistent coal zones were also identified which are referred as the Upper Strays, Inayatabad, Wassi and Lower Strays. A total of 12 coal seams are found in the area. The coal seams are almost horizontal, slightly dipping towards the west at 2°.

According to the GSP, the estimated ranks of the coal are lignite A to subbituminous C. Regardless of the overburden, there is no terrain hindrance to mining (SanFilipo et al., 1994). Hydrologic connectivity of the area, with its waterlogged bodies along the Indus River, was determined to be likely (Abbas & Atique, 2005). Fig. 2 shows a generalized stratigraphy of the Sonda-Jherruck coal field (SanFilipo et al., 1994). A total of 7.612 billion tons of coal resources were reported. Coal resources were calculated using a modified version of the "extrapolated bed method" (Wood, Kehn, Carter, & Culbertson, 1983). However, no resource modeling was carried out.

Reliable mineral resource estimation is critical to both confidence in a feasibility study and to the day-to-day mining operation. Thus, high-quality interpretation and estimation are needed. Several methods used for solid modeling and fault modeling were reviewed in order to model the entire coal field by effectively utilizing the drill hole data. (Siddiqui et al., 2015) generated a 3D solid seam model by digitizing coal seam intercepts in numerous geological sections to estimate the Thar Field, Pakistan. Akiska, Sayili, and Demirela (2013) successfully modeled the surface and subsurface zones in 3D using topographic and drill hole data, respectively, for the Handeresi area located in the Biga Peninsula, Turkey by using insufficient and unusable data. Caumon, Collon-Drouaillet, De Veslud, Viseur, and Sausse (2009) built a 3D structural model of geological interfaces, such as horizons and faults, using available observation data. Luo, Xiao-ming, Jia-hong, Ya-bin, and Wang-ping (2007) built a reliable orebody model from drill hole data. The 3D fault models were constructed based on prospecting cross-section plane sheets, and the volume of the mining cavity was estimated using ordinary kriging method. Lemon and Jones (2003) also constructed solid models using the horizon method by assigning horizon IDs to each of the drill hole contacts and then interpolating each of the defined surfaces and digitized solid seam models. Deutsch &and Wilde (2013) developed an approach of 3D modeling relatively large multiple coal seams using the signed distance function, without generating surface elevations models. The risks associated with lignite reserve estimation were assessed using semi-variograms and conditional simulation by Pardo-Igúzquiza, Dowd, Baltuille, and Chica-Olmo (2013) in North-western Spain. Wu et al. (2005) proposed a method to simulate geological structures without sufficient data. The multi-source data integration refines 3D models to the desired accuracy. Zhao, Bai, and Liu (2011) constructed solid models with the mergence method, and their fault model was generated by defining fault lines in contour maps of the top and base of the coal seam. Tercan et al. (2013) used two approaches: the section method and top-bottom surface method for the seam modeling of the Eynez-Soma and Ömerler-Tunçbilek coal fields in Turkey and detected faults with a combination of both methods. Wu and Xu (2003) proposed a novel approach to estimating and construing the geometric shape of a fault based only on the 3D coordinates of two fault points, the dip and the direction of the fault. The drill hole data is also used to identify fault zones. Gribble (1994) formed an effective model to define the faulting pattern by calculating the dip between the data points. To regularize the data, an appropriate grid on the digital terrain model (DTM) of the

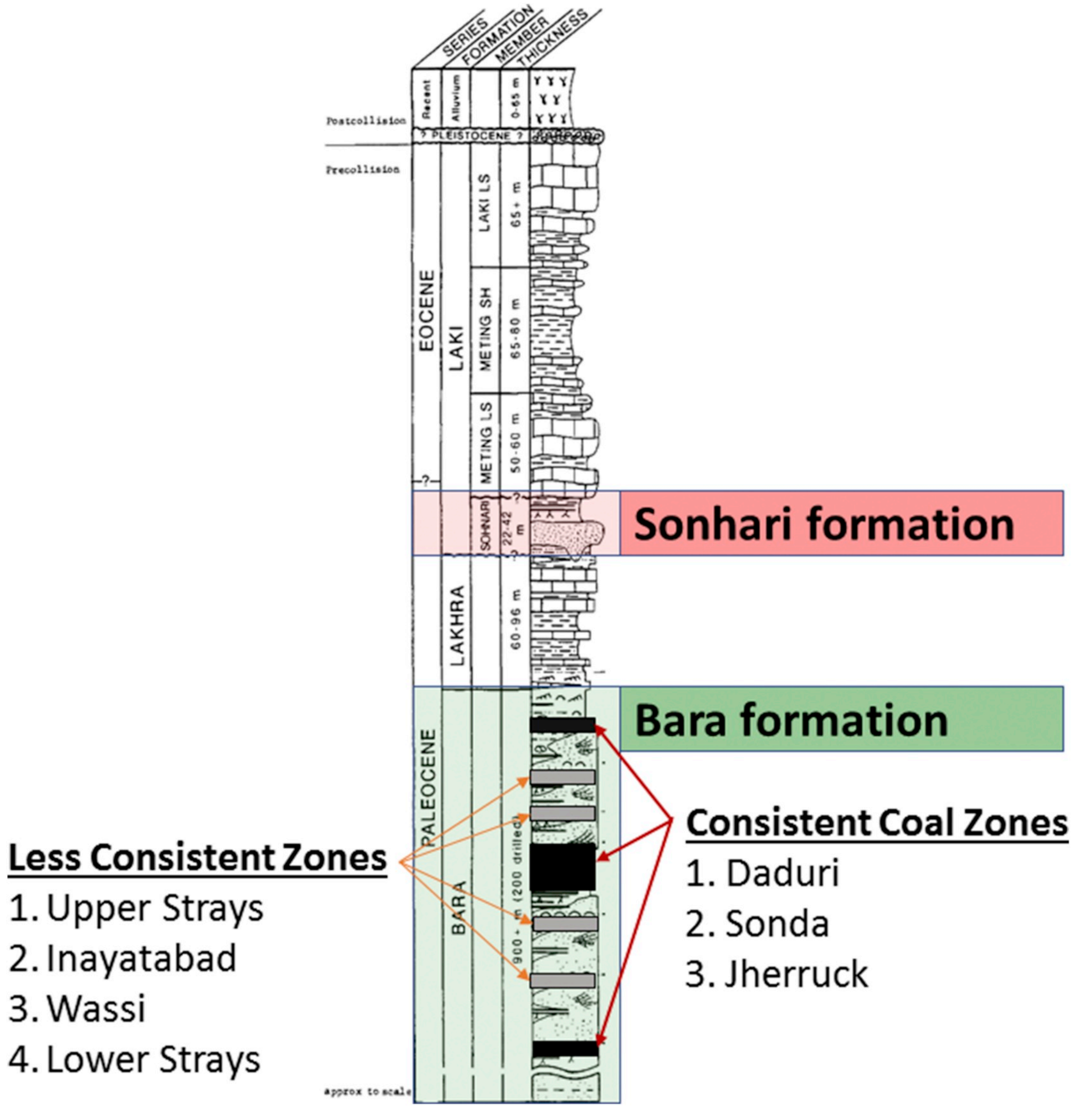

Fig. 2. Generalized stratigraphy of Sonda-Jherruck coal field, Pakistan.

Table 1
Structure of the datasheet of the geologic database.

Table	Fields						
Collar	hole ID	northing	easting	elevation	depth	n/a	n/a
Survey	hole ID	depth	northing	easting	elevation	dip	azimuth
Geology	hole ID	sample start point	sample end point	rock type	seam code	n/a	n/a

Table 2
The details of drill hole information.

No. of drill holes	Average drill hole space (m)	Depth (m)		
		minimum	maximum	average
72	2700	55.62	366.34	214.15

surface was overlain. Ünal, Ünver, Hindistan, Ertunç, and Tercan (2013) also proposed a fault detection method based on dip calculation. The drill hole data was used to create a surface, the surface was divided into squares and the dip and dip direction values were calculated for each square. The kriging and co-kriging methods were used to generate the variation of dip and dip directions.

This paper presents the solid modeling of multiple coal seams and an improved fault detection method, used with a focus on the identification of fault zones in the field. The previous exploration results were improved by using the data more efficiently with a new approach which effectively highlights faults in the area. The developed seam models can be used to improve further decisions regarding future exploration targets and mining plans, and to identify other potential problems.

2. Materials and methods

2.1. Exploratory data analysis

Publicly available data for 72 exploratory drill holes generated from

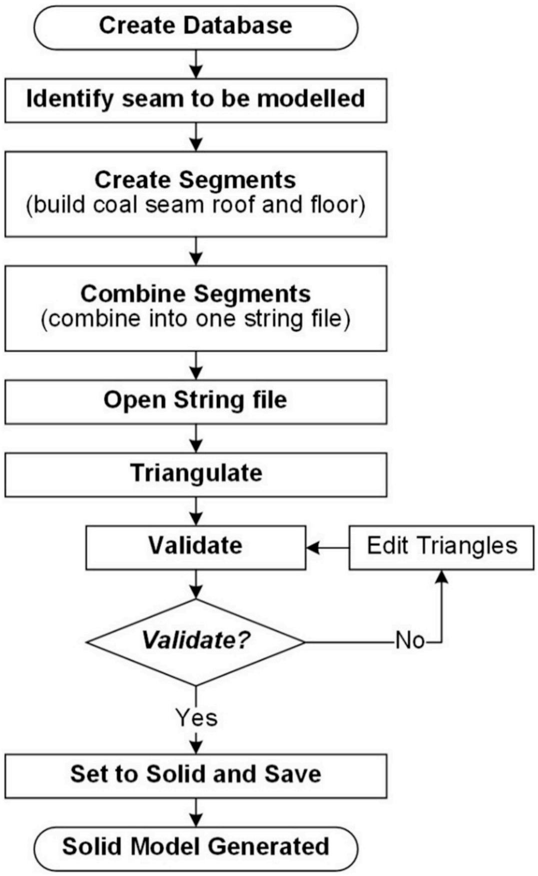

Fig. 3. Flow diagram of steps used to generate the solid model.

GSP and USGS reports was used in this study. The data was statistically analyzed to determine the basic characteristics. The minimum, average and maximum depths of drill holes were recorded as 55 m, 214 m and 366 m, respectively. The average drill hole spacing was calculated as 2700 m. The main Sonda seam (S) is present in 61 drill holes with an average depth of about −162 m from mean sea level (SSTVD). The data contains the location, orientation and lithology of the area. After initial spot-checking of digital records, a comprehensive review and validation of the entire digital dataset was completed by checking all the database entries including the collar coordinates, survey values, hole depth, lithology codes, etc. A complete database was prepared for the solid seam and fault detection modeling. Table 1 shows the structure of the datasheet. The details of the drill hole information are given in Table 2.

2.2. Solid modeling

A solid model was constructed from non-overleaping triangles of data that can be interpreted easily and efficiently. Two methods of solid modeling are normally used; the sectioning and the top-bottom surface modeling methods. In the section method, the coal seam is outlined vertically in sections and then combined to create a solid 3D model. In the top-bottom modeling method, the top and base surfaces of the coal seam are triangulated and then combined. In this study, the top-bottom surface method was used to model the coal field and to enable the discussion in detail of the occurrence and distribution of the coal resources. Models were created using GEOVIA SURPAC. Fig. 3 shows the flow chart of the methodological framework involved in creating a solid model. The spatial distribution of the individual seam thickness is determined from the block model by summing the individual block thickness in each block column in a downward z direction.

2.3. Fault modeling

It is essential to thoroughly understand the fault zones in order to know the real hazards and obstacles in mining and engineering work. In this study, the methodology proposed by Ünal et al. (2013) based on dip calculation was followed and implemented for fault interpretation. This method of fault detection provides reliable results from the drill hole data. Dip angles were calculated on a regular grid and estimated at unobserved locations. The top of the main seam encountered in all drill holes was digitized and the created surface was then put into a grid of equal squares. The coordinates of each corner point of the square were determined using the x, y and z values, and the maximum dipping was calculated by an algorithm created in Microsoft Excel. The data acquired from the algorithm is then used as input to SURPAC for block modeling. Dip angles of 30 different lines for a typical square were calculated using Equation (1). A block model that includes all the maximum dip data was prepared. In and around the fault zones, a high variation in the amount of elevations can be clearly observed. Differentiation around the fault zones was analyzed by evaluation of the maximum dips. The fault modeling methodology is shown in Fig. 4.

$$Dip = tan^{-1}\left(\frac{z_2 - z_1}{\sqrt{(x_2 + x_1)^2 + (y_2 + y_1)^2}}\right) \quad (1)$$

A block model was created and the dip values were estimated using the centroid dip grid using the inverse distance squared weighting technique (IDW^2).

3. Results and discussion

Daduri 1 (D1) is the upper coal-bearing seam and the Daduri 2 seam lies beneath it. These seams are mostly concentrated in the Indus East part of the area. Upper strays (USTR) is found in the Indus East area as well as in the Sonda Area along Keenjhar lake. The Inayatabad (I) coal seam is present in the western area of the field. The Sonda Upper (SU) seam is mostly concentrated in the eastern part of the coal field. The majority of the area in the coal field map is covered by the Sonda main seam (S) whereas the Sonda Lower Main seam (SSL) shows the thickest seam region in the northern part of the field. The Sonda lower (SL) seam is found in a small area of the field to the south-west east. The Wassi (W) seam is found in the west and the east part of the field. Lower strays (LSTR) lie mainly in the Indus East part, whereas a small concentration is also found in the Sonda-Thatta area. Jherruck (J) is the deepest coal seam, found in the eastern part of the area. Fig. 5 presents the thickness profile of the coal seams.

Coal resources in this study are categorized into two groups; total in-place coal resources and mineable coal resources. The minimum seam thickness criteria of 0.3 m was used for the resource estimation of the total in-place coal resources whereas the thickness of 1.3 m was taken as the mining constraint for mineable coal resources. Table 3 summarizes the total in-place and mineable coal resources of the Sonda-Jherruck coal field. It can be seen that the Sonda main seam contains abundant in-place coal resource of 1675 million tons, out of which around 38% is mineable. 86% of the 800 million tons of the total in-place coal resources of the Sonda Lower Main seam is mineable.

The dip map for the entire Sonda-Jherruck field was generated and compared with the existing USGS fault lines (shown in Fig. 6). USGS fault lines observed in aerial photos are shown in Fig. 7. The faults take

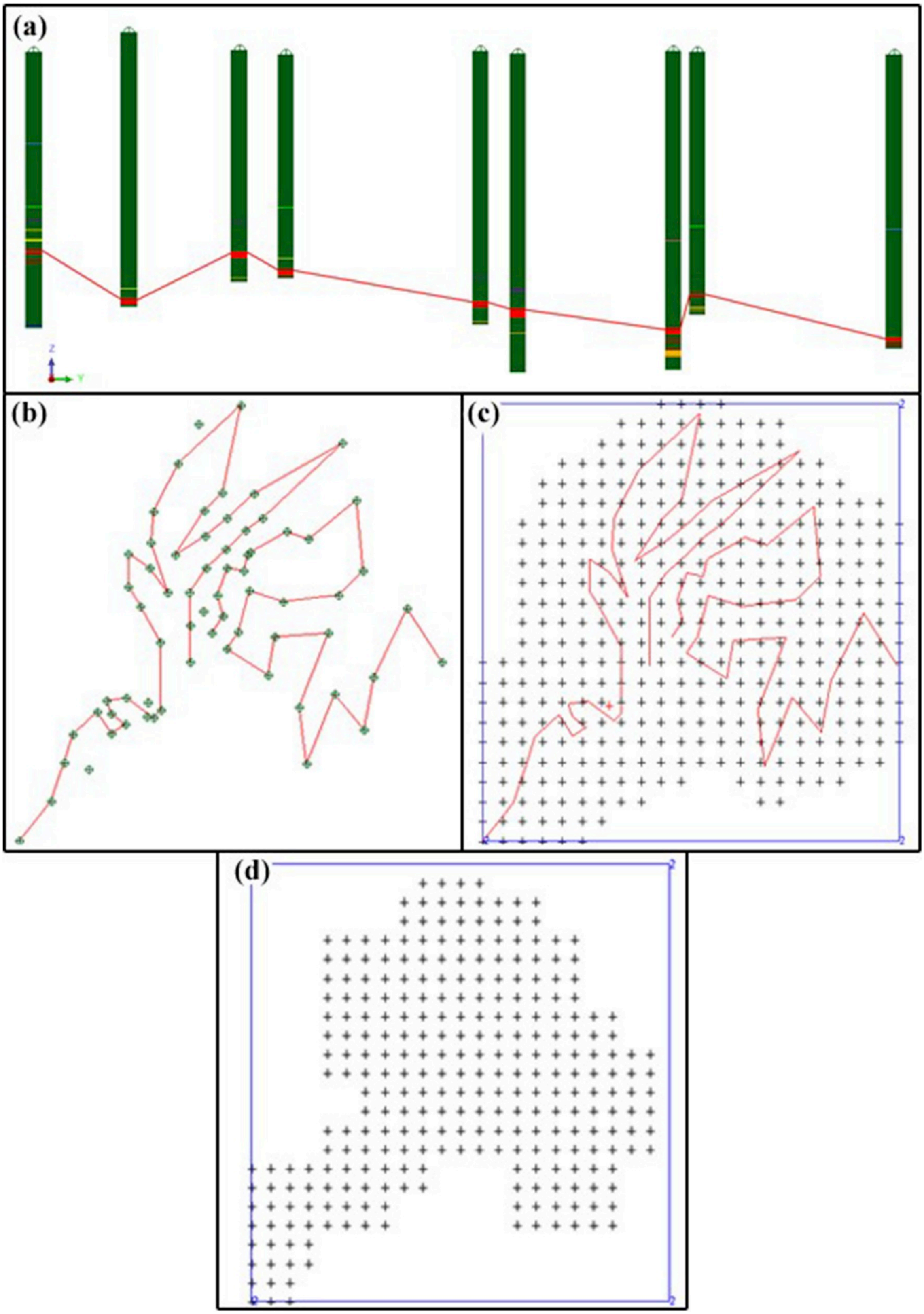

Fig. 4. Fault modeling methodology adopted from Ünal et al., 2013 a) Digitized seam tops, section view b) Digitized seam tops, plan view, c) IDW Gridding d) Centroid Dip values.

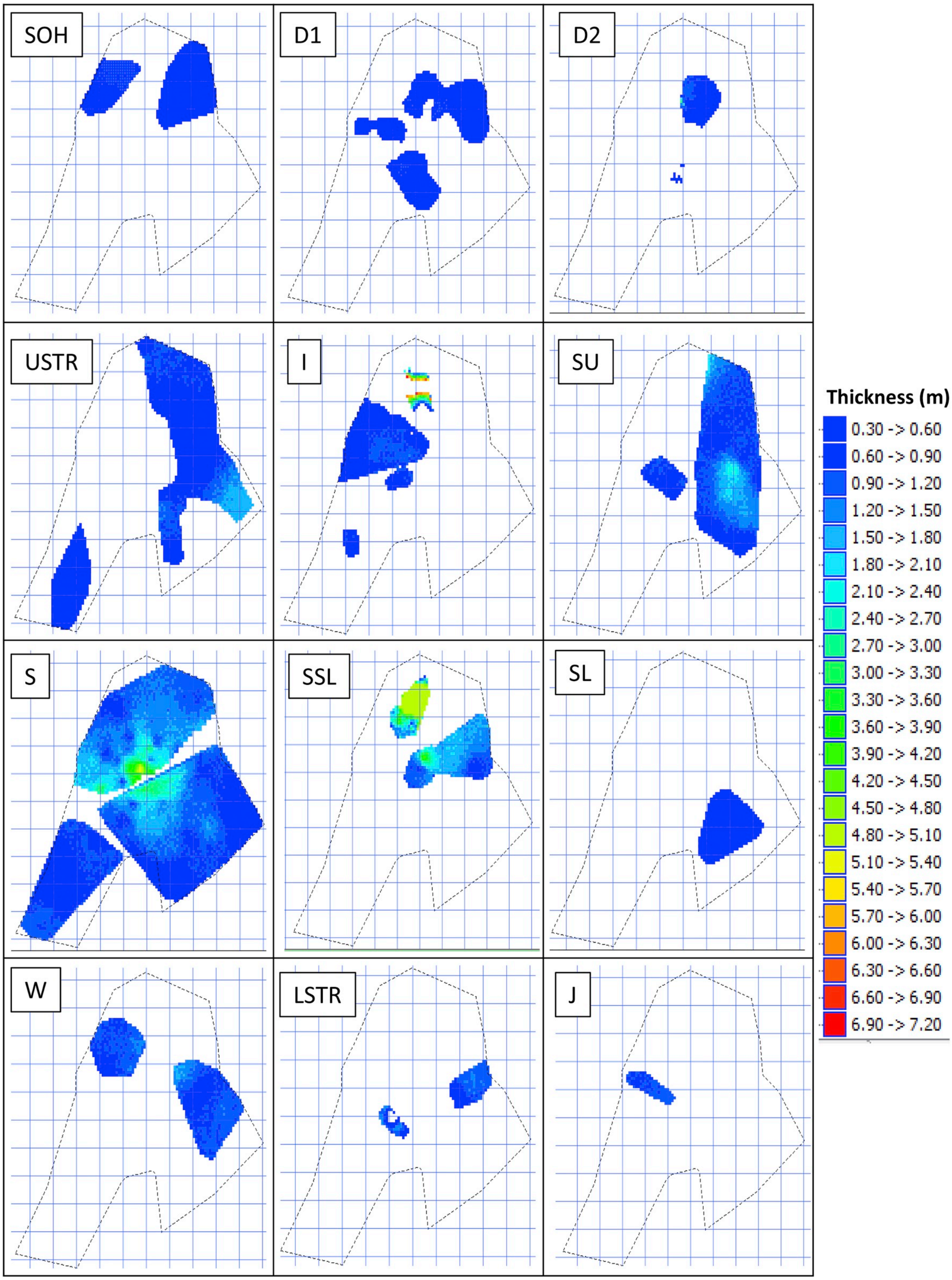

Fig. 5. Thickness map of coal seams.

on a range of orientations from vertical to horizontal. The dip is the angle that describes the steepness of the fault surface.

4. Conclusion and recommendations

Pakistan is not technologically advanced in the digitization and numerical modeling of the mineral sector, including exploration, planning, designing, and mine development and instrumentation. In order to fulfill exponentially increasing energy needs, Pakistan must consider the development and exploitation of its indigenous resources. This paper aims to assess the Sonda-Jherruck coal field and to identify the most promising areas within the field to initiate full-scale

Table 3
Total in-place and mineable resources of the Sonda-Jherruck coal deposit.

Seam Nomenclature	Seam Code	Total in-place resources (million tons)	Mineable resources (million tons)
Sohnari	SOH	143	–
Daduri 1	D1	148	–
Daduri 2	D2	64	2
Upper Strays	USTR	443	62
Inayatabad	I	419	82
Sonda Upper	SU	539	105
Sonda (main)	S (main seam)	1675	643
Sonda Lower Main	SSL	800	693
Sonda Lower	SL	63	–
Wassi	W	268	7
Lower strays	LSTR	67	–
Jherruck	J	33	–
Total		**4662**	**1595**

exploration for integrated coal mining operations. The obtained solid seam models establish substantial in-place resources of 4.66 billion tons of resources, of which 1.59 billion tons are mineable. The obtained thickness maps will help to devise further exploration and exploitation strategies. The method of fault modeling used in this research demonstrates good understanding of the fault zones in the area. The identified fault zones were compared with the USGS fault lines and significant agreement was observed.

It was observed that most of the coal resources in the western part are mineable. Coal lies between water bodies and consequently they may represent a hurdle for mining operations in the future. Potential mine flooding could constrain mining. Mining may not be performed using conventional surface methods because of the depth of the coal seams. Additional exploration work is highly recommended in the areas with higher uncertainty.

Deep drilling is recommended with 1 km average drill hole spacing in order to provide better output. It is also recommended that at least one exploratory drill of at least 500 meters in length be completed to confirm the availability of more coal zones. Sonda-Jherruck is surrounded by water bodies, so hydrological studies should be carried out to avoid mine inundation.

Ethical statement

Authors state that the research was conducted according to ethical standards.

Funding body

Not applicable.

Conflict of interest

Authors state that there is not any conflict of interest.

Acknowledgements

The authors are thankful to Mehran University of Engineering and Technology, Jamshoro for providing necessary equipment and software for the conduct of this research work. Authors are also indebted to Dr. Bahtiyar Unver and Engr. Suphi Unal from Hacettepe University, Turkey for providing clarification and guidance on Fault detection methodology.

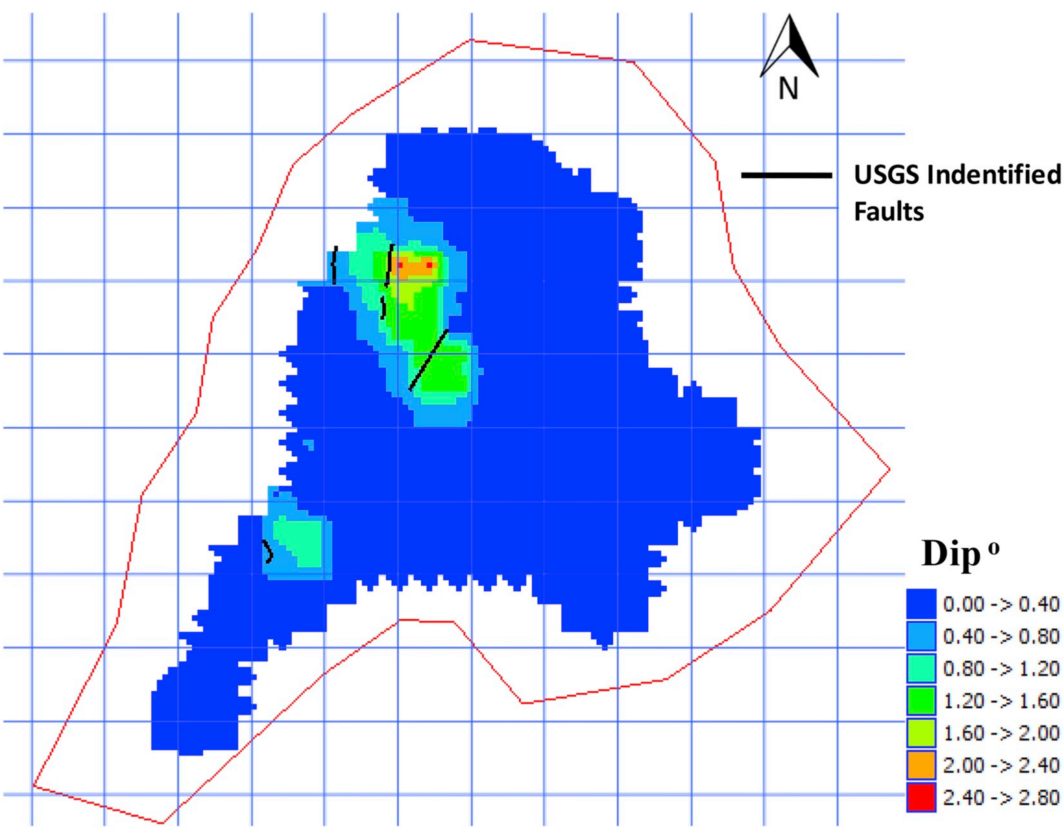

Fig. 6. Potential fault zones based on dip changes (USGS identified fault zones are superimposed for comparison).

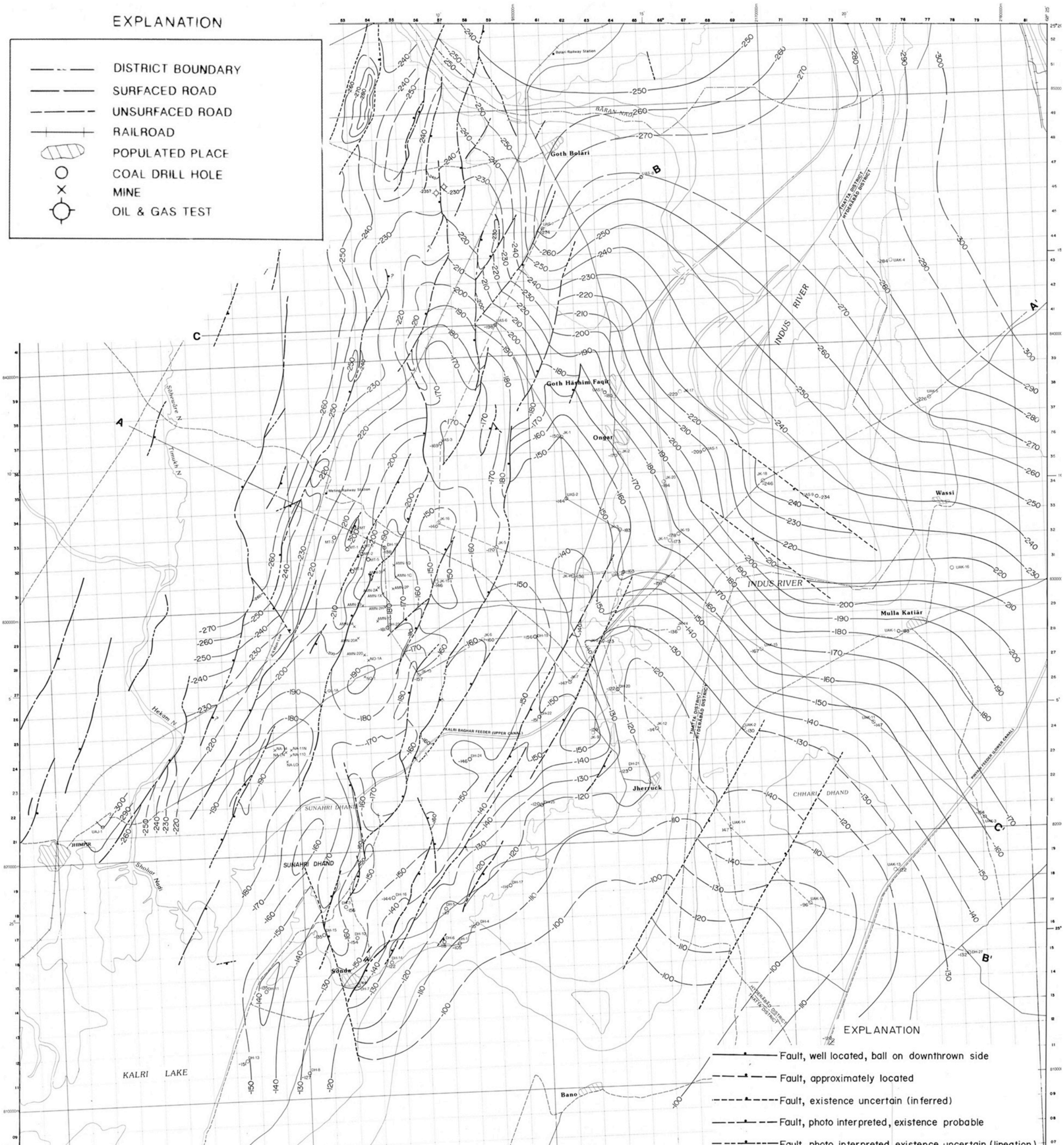

Fig. 7. USGS faults lines observed on aerial photos.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jsm.2018.06.001.

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