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An Overview of Pakistan Rock Salt Resources and Their Chemical Characterization

Syed Asim Hussain[abcd]*, Han Feng-Qing[ac], Ma Yunqi[ac], Hawas Khan[d], Yang Jian[abc], Gulfam Hussain[e] and David Widory[f]

[a]Key Laboratory of Comprehensive and Highly Efficient Utilization of Salt Lake Resources, Qinghai Institute of Salt Lakes, Chinese Academy of Science, Xining-810008, China
[b]Qinghai Provincial Key Laboratory of Geology and Environment of Salt Lakes, Xining-810008, China
[c]University of Chinese Academy of Science, Beijing-100049, China
[d]Department of Earth Sciences, Karakoram International University, Gilgit-15100, Pakistan
[e]Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing-100101, China
[f]GEOTOP/Earth and Atmosphere Sciences Department, UQAM, Montréal, Quebec, Canada

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Abstract. Rock salt is of importance for both humans and industries. In this study, we discussed the main salt deposits in Pakistan by evaluating the total reserves as well as the rock salt annual production and by characterizing their chemical composition (Na^+, Ca^{2+}, Mg^{2+}, K^+, B^+, K^+, Li^+, Cl^-, SO_4^{2-}, Br^- and NO_3^-). Our objectives were to document their impurity, water-insoluble matter and moisture contents to ultimately discuss whether the halite in Pakistan, in its natural form, is safe for human consumption. Pakistan rock salt deposits are located in two distinct regions: the Salt Range area in the Potwar sub-basin with huge Precambrian salt deposits and the Eocene Bahadurkhel/Kohat salts in the Kohat sub-basin. Total reserves are estimated over tens of billion tons with an annual production of about 3,534,075 metric tons in 2017-18. Results show that the halite of the salt range area is purer than the Bahadurkhel/Kohat salts with purity levels (expressed as NaCl) of 99 and 95 wt. %, respectively. Gypsum represents one of the main impurities in halite for both regions, while potash salts (>9 wt. %) are observed in the Salt Range area, K contents are very low in the Kohat salts. Although the halite moisture content is similar for both regions, impurities contents are higher (>5%) for the Kohat salts, arising the need for their purification prior to eventual human consumption.

Keywords: Kohat-Potwar Plateau, rock salt, reserves, chemical characterization

Introduction

Rock salts, commercially referred as (mineral) halite is chemically NaCl (about 39% Na and 60.5% Cl). Halite is one of the most vital constituent of mineral evaporites series. Generally, it is a product of concentration and precipitation processes from seawater under arid conditions. It is in close relationship and always co-precipitates with industrial minerals such as gypsum, potassium and magnesium salts.

Pakistan possesses the world's largest salt deposits, with proven reserves of over ten billion tons that display a 98% purity. The major salt deposits are mainly exposed in the Kohat-Potwar plateau of the upper Indus (Krishnan, 1966). The oldest salt deposits (Edicambrian age) are only exposed in the salt range area (southern border of the Potwar sub-basin (PB) and are known as the salt range formation or the Punjab Saline Series. The younger Eocene salt deposits are located in the Kohat sub-basin (KB) and are referred to as the Bahadurkhail salts or the Kohat saline series (Fig. 1).

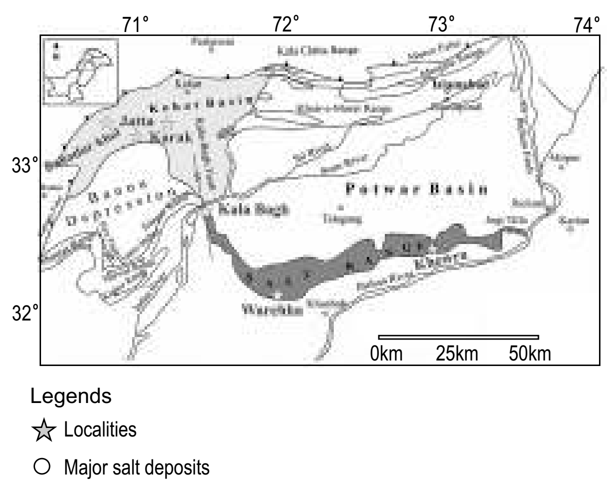

Fig. 1. Distribution of major rock salt deposits in the Upper Indus Basin (Pakistan).

*Author for correspondence; E-mail: s.asim@isl.ac.cn; s.asim_110@yahoo.com

The salt range formation (SR Fm.) represents the local Precambrian geology, which includes the world thickest salt stratum ~2000m (Hussain *et al*., 2020). Typical SR Fm. can be described from the formation exposed at the Khewra Gorge. Due to its huge thickness the base of the SR Fm. is not exposed. It is further divided (Fig. 2) into the following three sub-members:

Billianwla salt member (oldest member, base not exposed); Bandarkas gypsum; Sahwal marl.

In comparison, the Bahadurkhel salts in the Kohat sub-basin (KB) are thin compared to the SR Fm. and can be observed at different locations (Jatta, Karak and Bahadurkhel) of the KB. Just like the SR Fm. its base is also not exposed but its thickness is variable, with a maximum of 700m in the Shakarkara village (Hussain, 2020; Pivnik and Wells, 1996; Asrarullah, 1963).

Due to their purity, the demand for Himalayan salts has increased in recent years, concomitantly increasing, its production, but still only representing 0.88% of the salt world production (Brown *et al*., 2017; Brown *et al*., 2013), remaining at the 20th rank in the world salt exports. As rock salts generate important commercial revenues for Pakistan, they have been widely studied. Especially, the upper Indus basin (UIB) has been widely studied for its Pre-cambrian stratigraphy, the Permian-triassic marine belt, the tertiary foraminiferal bio-stratigraphy, the tectonic closure of the Tethys sea and the wide spread salt and gypsum deposits. The SR and the adjoining geologically related areas of the UIB were first surveyed by Wynne (1880, 1878 and 1875). Gee (1947, 1945, 1938) early 2 inches to 1-mile geological maps were later updated to the scale of 1:50,000 (Gee and Gee 1989; 1983 and 1980), also contributing to determining the age of saline series. Pakistan rock salt resources were estimated by Asrarullah (1963, 1962), Alam and Asrarullah (1973). Qadir *et al*. (2005) worked on the quality of the Kohat salts and developed a technique for characterizing its purity. Sharif *et al*. (2007) studied the chemical evolution of major rock salts (Kohat, Khewra and Kallarkahar salts) as well as lake salts (Tharparker). Hassan *et al*. (2016) chemically characterized unrefined salts from the Kohat basin (Jatta and Bahadurkhel deposits), rock salts from the salt range (Hassen *et al*., 2017a) as well as heavy metals in refined salts of Pakistan (Hassen *et al*., 2017b). On the other hand, Hussain *et al*. (2020) used elemental and isotope geochemistry to characterize their purity and the paleoclimate conditions that prevailed during their deposition.

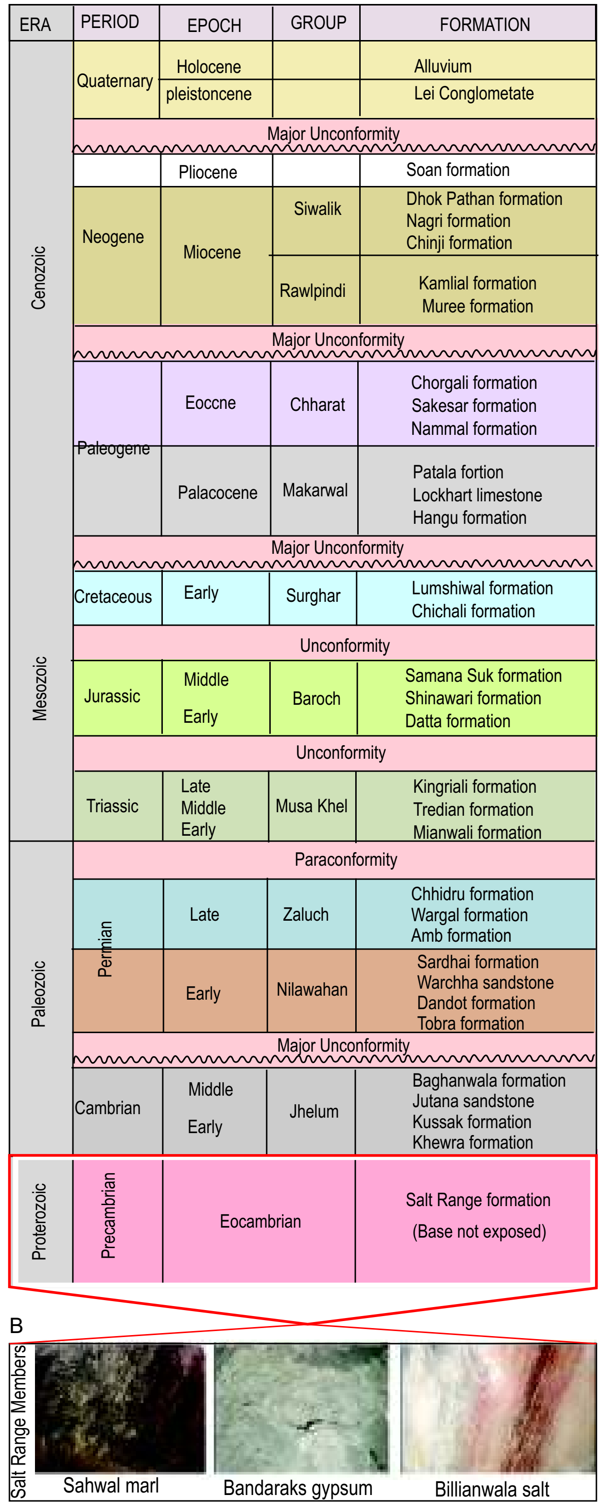

Fig. 2. (A) Stratigraphic column of the different geological units in the study area (after Grelaud *et al*., 2002). (B) Pictures of the Pre-cambrian salt range subdivisions (after Ghazi *et al*., 2015; Sameeni, 2009).

Still, to our knowledge, the chemical characterization of the Pakistan halite and its link to the regional geology is missing. In this study, we aimed at providing a clear relationship between geology and the halite characteristics, in order to ultimately be able to issue recommendations for its human use. This will provide a baseline for future rock salt research in Pakistan. With that in mind, we studied the main Pakistan salt deposits, located in the Southern Himalaya and Western Pakistan, with the objectives of estimating the total reserves as well as the annual production and of characterizing their chemical compositions to document their impurity contents.

Study area and regional geology. Among the numerous Pakistan basins, the Indus basin is one of the largest (Fig. 3). It covers an area of about 533,500 km^2 and contains over 15,000 m-thick sediments bridging from the Pre-cambrian to recent ages (Kazmi and Abbas, 2001). Based on its tectono-stratigraphy, the basin is divided into three zones (Kazmi and Jan, 1997), (1) the southern or lower Indus basin, (2) the central or middle Indus basin and (3) the northern or upper Indus basin (Fig. 3).

The Jacobabad-Khairpur area represents the division point between the middle Indus and the lower Indus basins. The region between the Mari-Khandkot highs (Sukkur rift zone) and the Sargodha highs (Sargodha-Shahpur buried ridge) is known as the middle Indus basin, and towards the north direction, the region located between the Sargodha high and the MBT forms the upper Indus basin also known as the northern Indus basin. The upper Indus basin can be subdivided into two sub-basins: the Potwar (PB) and the Kohat sub-basins (KB) that together form the Kohat-Potwar plateau. The Kohat-Potwar Plateau is separated into the KB and the PB by the Indus river (Fig. 1). It is bounded to the north by the Kalachitta-Margalla hill ranges and to the south by the salt range, and the Trans-Indus Ranges mark its boundary (Kazmi and Jan, 1997). The main sources of Pakistan rock salts are located in these two sub-basins (PB and KB, Fig. 1). In the Potwar sub-basin, the Pre-cambrian salt range is considered as the main and oldest salt deposits in the sub-continent, which extends several hundreds of kilometers within the Potwar plateau. Its thickness has been recorded as higher than 2000 m in a drill hole in Dhariala, about 400 km north of Khewra (Sameeni, 2009).

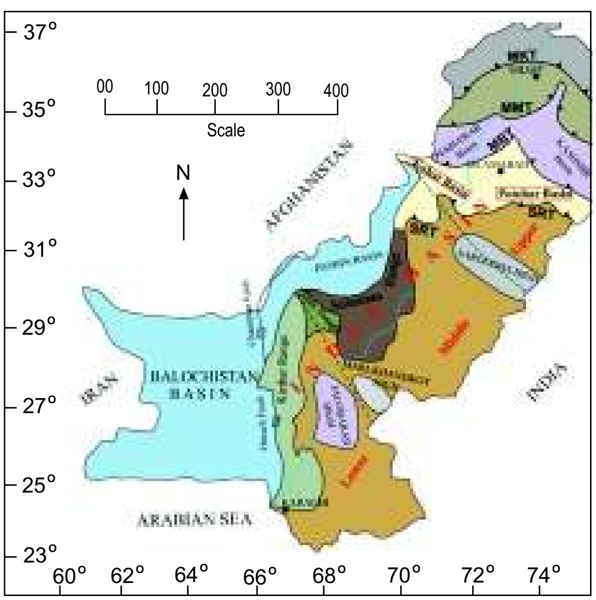

Fig. 3. Major Pakistan basins and divisions of the Indus basin. KB=Kohat sub-basin and PB=Potohar sub-basin (Modified from Hussain, 2020; Kadri, 1994; Farah *et al.*, 1984).

The younger salt deposits (Eocene age) are found in the northwestern Kohat basin with the main deposits located in the central part of the basin. The exposed thickness varies from place to place, up to 120 m (Meissner, 1974). Deposits contain halite along with variable amounts of gypsum dolomite and clays, and limited layers of potash and magnesium salts.

Geologically, regardless of their small sizes, the two sub-basins present variable and important sequences and records of the collision between the Indian and Eurasian Plates (Kadri, 1994), about 67±2 Ma (Powell *et al.*, 1998). The PB exposes the geology and stratigraphic events (Fig. 2) preserved from Pre-cambrian to recent ages, and all these features are exposed in the salt range (SR) area. The PB is mostly covered by the Siwalik group, however upper Eocene shales and limestones locally crop out in folded inliers. The northern part of the PB, also identified as the north potwar distorted zone (NPDZ) is more strongly twisted and deformed. Complex and tight folding (east-west) and steep faults are the main characteristics of this region. In the KB, the Paleocene-Eocene strata are fairly complete. The Eocene system mainly contains evaporites (Bahadur Khel salt and Jatta gypsum) that are limited to the southern part. The structure style in the northern and southern KB is different: the overturned folds, out of syncline faults, thrust and reverse faults are the most prominent structural features.

In the SR area, the SR Fm. is mainly exposed along two long chains: (1) along the southern rim of the SR scarps, and (2) along the cores of transverse anticlines traversing the escarpment. The Khewra area is an asymmetrical dome shape, cut by the Khewra stream that exposes a significant stratigraphic part of this area. A complete sequence of the SR Fm. is exposed (Table 1) about one km from the mouth of the Khewra salt mine. All the strata exposed in the Khewra salt mines are part of the lower or main saline marl. Faults in their southern and western parts limit its extension. All corresponding seams are divided into seven distinct seams (Fig. 4), three in the upper group called the Buggy complex and four in the lower group called the Pharwala complex (Bilgrami, 1982). These two groups are separated by a layer of interbedded (salt and marl) seams. The Buggy complex group includes (1) the north Buggy salt Seam (2) the Buggy Seam and (3) the Sujjawal Seam. The Pharwala complex includes (1) the upper Pharwala Seam (2) the Middle Pharwala Seam, (3) the south Pharwala Seam and (4) the Low-level tunnel Seam.

Faults control the overall structure of the Warcha area. Due to thrust faulting, the salt-bearing marl of the SR Fm. is directly overlaid by the carboniferous lavender clays. On the western side of the deposit, salt marl is thrust-faulted against Mesozoic formations and the limestone overlies. On the eastern side of the deposit, due to the presence of numerous strike faults, the salt intersperses with sandstone. The salt bands in Warcha are considered thin compared to those of the Khewra region (Asrarullah, 1963; Gee, 1946; 1938). The thicknesses of the different rock sequences are given in Table 4.

The Kalabagh area of the salt range is geologically very complex with tight folds and high angle faults (including the Kalabagh fault). In Kalabagh the SR Fm. crops out at the foot of the slopes of the hill to the east, south (towards the Indus), and southwest (towards Kalabagh city) directions. The SR Fm. is overlaid by complex strata ranging from upper carboniferous to Pleistocene. Rocks older than Pleistocene (Triassic to Eocene) crop out on the western slope in northern Kalabagh. The rock salt beds are thinner and irregular compared to the other two main deposits of the SR area. This results, to some extent, from complex depositional conditions, coupled to the fact that the salt beds themselves have been later re-twisted by tectonic forces. Consequently, salt beds are often contorted and lenticular, and the corresponding dips are steeper and irregular, reaching angles as high as 65° (Asrarullah, 1963).

In the KB, the Eocene rocks extend up to 40 km in the NS direction. The basin is more complex and displays more geological variations compared to the Potwar

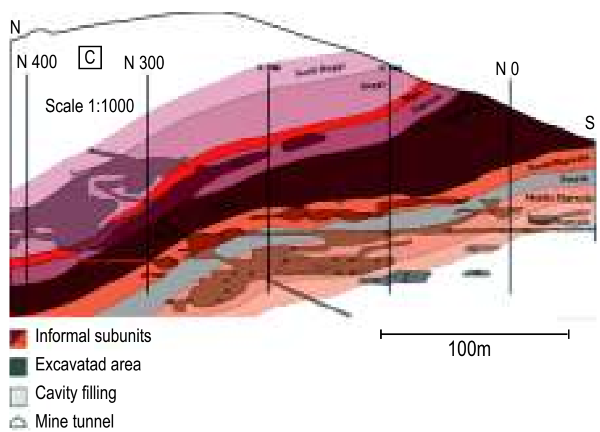

Fig. 4. Study area and distribution of informal sub-units of the salt range formation in the Khewra mine (after Hussain *et al*., 2020; Richards *et al*., 2015).

Table 1. Rock order in the salt range Fm. at the Khewra gorge. New divisions are taken from Sameeni (2009) and the old ones from Asrarullah (1963)

Stratigraphy sequence(s)		Subdivision/Description	Thickness (m)
New division	Old division		
Sahwal Marl	Upper gypsum dolomite	Crystalline to non-crystalline	0-20
	Upper saline marl	a) Bright red marl + minor salt seams	>80
		b) Dull red marl + gypsum (3m at top)	50
Bandrakas gypsum	Middle gypsum	Crystalline to non-crystalline	50
Billianwala salt	Lower or main saline marl	Halite + sometimes intermixed with gypsum beds	>650
	Lower gypsum dolomite	Base is not exposed	>100

Note: Thickness and the lithology of the exposed rock from the Khewra salt mine are presented.

basin. The structure is highly tight folded with complex faults and narrow anticlines. The salt deposits are exposed along these anticlines following a general EW trend and crops out in the center of the KB in the Manzalai anticline and along the Karak-Hukni Fault system as diapirs overlaid by the Jatta Gypsum (Pivnik and Wells, 1996). The base of the salt is not exposed and its thickness is unknown. However, a hole drilled in the core of an anticline in the Shakarkara village revealed about 700 m of salt that might be due to over-turn folding. Still, correlating the age of the salt with the age of the geological units (e.g. the Ghazij group) is difficult due to a lack of age control. Locally, the salt contains highly petroliferous, black, asphalt-like, carbonaceous materials. According to Pivnik and Wells (1996), the formation of rock salts in the KB results from the warm brine initially deposited in the center of the basin and moved later on to its southern part by high density and tectonic actions. The exposed tertiary (Paleocene and Eocene) stratigraphic units are given in Fig. 5.

The exposed rock salt thickness in the Bahadurkhel (KB) area is about more than 105 m, while in the Jatta and Karak areas it is ~35m (Qadir *et al*., 2005). The salt is grey with a translucent and compact texture. It also contains thin dark grey bituminous beds along with thin inclusions of dark bituminous salt (Asrarullah, 1963).

Materials and Methods

Sampling. We collected halite samples for chemical characterization from all the major deposits. Details about the sample locations are given in Fig. 1. We selected unweathered and the most representative possible halite samples.

Processing procedures. In this study, all samples were selected on the basis of their quality to characterize the following parameters i.e. moisture content, water-insoluble matter, calcium, magnesium, sulfate, nitrate, lithium, bromine and boron contents. All analyses were performed at the salt lakes Analytical and Testing Department, Qinghai Institute of Salt Lakes, Chinese Academy of Sciences. Halite samples were first dissolved in deionized water (deionized at least four times). We prepared each sample to ultimately obtain a solution having a TDS (total dissolved solid) of ~ 200 mg/L (Han *et al*., 2019; Hussain *et al*., 2019). K^+, Ca^{2+}, Mg^{2+}, Li^{3+} and B^{3+} concentrations were measured by Plasma spectrometry (ICAP6500DUO, USA (Jibin *et at*., 2020; Hussain *et al*., 2019) with an analytical error of less than ±5%. Br^-, NO_3^- and SO_4^{2-} concentrations were determined by Ion Chromatography (IC-5000+, Thermo Fisher USA; error <1.0%) and Cl- by chemical mercurimetry (with an accuracy higher than 0.3%) (ISL, CAS, 1988). Water-insoluble matter was determined by gravimetric methods and the moisture content by heating methods (Hassen *et al*., 2016).

Results and Discussion

The salt range deposits. The salt range (SR) covers an area of about 250 Km^2 between the Jhelum river in the east and the Indus river on its western edge. Rock

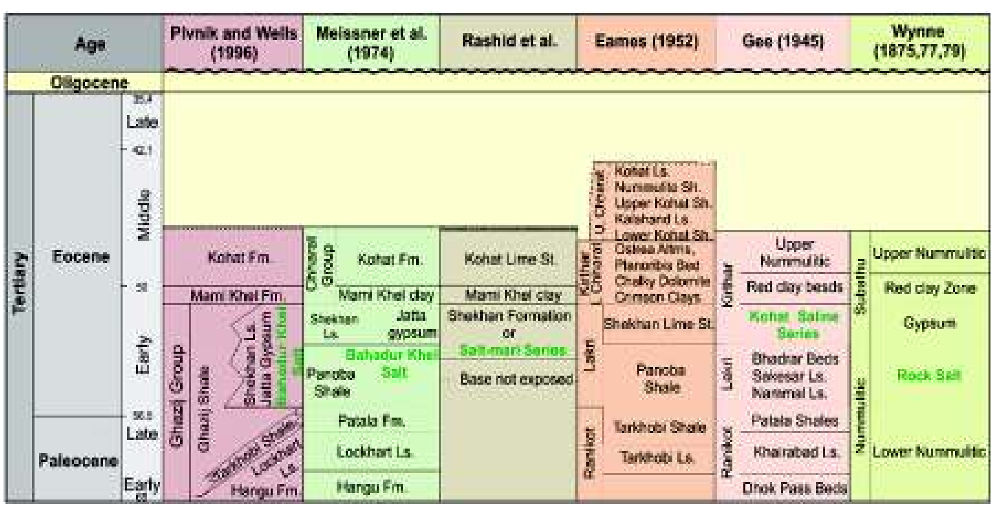

Fig. 5. Stratigraphic column of the Kohat Plateau for tertiary rocks. Absolute ages are from modified from Pivnik and Wells (1996) and Harland *et al*. (1989).

salts are generally found at the base of the escarpment-forming part of the salt range formation (previously known as the Panjab Saline Series). The base of the salt range formation (SR Fm.) is never exposed. The SR Fm. strata mainly contain a huge amount of gypsum, anhydrite, dolomite, red marl and salt. Generally, thick salt layers are interbedded and mixed with salt marl, which is locally known as "Khhallar", and beds of marl with impure potash layers. Even though rock salt outcrops can easily be found throughout the SR area, the main and bulk deposits are confined to the mines located at Khewra, Warcha and Kalabagh.

Khwera deposit. The Khewra salt deposits/mines are one of the oldest of the sub-continent and are located at the foothills of the salt range (PMDC, 2019). Salt is mined by the chamber and pillar method. Most chambers are about 17 m wide but a few are 12 m, and are horizontal and vertical in series across the strike of the beds (Asrarullah, 1963). At places, the salt occurs in the irregular dome-like structure. Structurally, the deposit can be separated into three zones from east to west: western, central and eastern parts. In the west, the strata inclination is very high (between 60 and 80°) towards the north and northwest directions. In the central part, strata are flattened out and dip towards the northeast, whereas in the eastern section strata are swinging in the east-west direction and dip south and southwest (Asrarullah, 1963).

Reserves and production. Although the Khewra salt mine has been exploited since 1872, by the mid-20th century the local miner thought it had exhausted. In the early 1960s, the Geological Survey of Pakistan (GSP) estimated the reserves at over 35 million tons in the mine and the total amount in pillars at 47 million tons (Asrarullah, 1963 and 1962). Later studies of borehole data indicated that the thickness of the SR Fm. was actually >2000m (Ghazi *et al*., 2012; Sameeni, 2009; Gee and Gee, 1889) and that, contrary to the general assumption, resources were unexhausted. Now, the reserves in the Khewra area are estimated at over a billion tons (PMDC, 2019). Still, the production was variable with time (1890-2018) and only recently reached its maximum (Table 2).

The Khewra mine gives rock salts with a purity of 98% (PMDC, 2019) with different shades: transparent, white, pink, and from reddish to beef-red. The mine is composed of 18 working levels and the cumulative drivage length is of more than 40 km (Sameeni 2009; PMDC, 2019).

Chemical characterization. Halite contains Na and Cl ions and is commercially sold as rock salt. Pure halite contains about 39 wt% Na and 60.5 wt% Cl (Sharif *et al*., 2007; Qazi *et al*., 2005). Rock salt is one of the basic minerals present in evaporate series generally linked with gypsum, Glauber’s salt, dolomite and potash salts (Han *et al*., 2018). Although previous studies (PMDC, 2019; Hassan *et al*., 2017; Sharif *et al*., 2007) showed that the purity of rock salts from the Khewra deposit ranges between 84 and 98% our analysis (Table 3) yields a slightly larger range, between 60 and

Table 2. Estimated reserves and annual production of all major salt deposits in Pakistan. Data are taken from Asrarullah (1963) and from PMDC, Pakistan (2019, noted by “*”)

Deposit name	Estimated reserves (million tons)	Year	Production (tons)
Khewra	-	1890	88184
	-	1945	251326
	>80	1960-61	149914
	Over 1000*	2018*	389134*
Warcha	-	1890	4409
	-	1945-46	52910
	>2.7	1960-61	35273
	>1000*	2018*	696038*
Kalabagh	-	1946	26455
	1.10	1961	17636
	-	2018	142540
Kohat salts	-	1870	18662
Kohat salts	-	1961	37324
4a	Jatta deposit > a few billions*	2018*	61109*
4b	Bahadurkhel and Karak > a few billions*	2018*	-

99 wt %. The less pure samples are either from the potash or from the Khallar (mixed salt and marl) layers. Potash salts are commercially more important. In most samples, the K^+ content is <1% but in the potash seam it can reach as high as 9.41%. The SO_4^{2-} contents vary from <1 to 27%, Mg^{2+} and Ca^{2+} up to 4.13% and 1.3%, respectively. SO_4^{2-}, Mg^{2+} and Ca^{2+} contents positively correlate with the K^+ content. Concentrations of elements such as B^{3+}, Br^- and NO^{3-} are < 1% in all samples. Concentrations of impurities and of the water-insoluble matter, in some samples, are about 5.1% higher than those reported by Hassan *et al*. (2017) but consistent with the study of Sharif *et al*. (2007), whereas the moisture content is =0.15% in all samples.

Warcha deposit. The Warcha deposit is the most productive one. It geologically lies on the southern scarp of the SR where the range has its maximum thickness (Fig. 1). The main deposit is located in Warcha mandi (Rukhla), a village about 3 km northwest of Warcha (Sarghoda division) in the central part of the SR.

Reserves and production. The Warcha mining history is dating back to the late 1800 (s) but the reserves had not been estimated until 1961. The total reserves estimated in 1961 are of about 27 million tons with an annual production of 0.044 million tons. Later estimation showed higher available reserves and the Warcha mine is currently the largest salt producing one in Pakistan with a higher rock salt quality of 98-99% (PMDC, 2019). The salts are generally available in three shades: transparent, white and pink. Recently, other mines were explored in the vicinity of the Warcha mine but their reserves and annual productions have not yet been estimated.

Table 3. Ion composition (in wt. %) of halite samples from the Khewra deposit

Sample	Loc.	Cl^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	B^{3+}	Br^-	NO^{3-}	Water insoluble	Moisture content
KH17-1	NLLT	51.05	6.96	36.41	0.32	0.23	0.13	0.00	0.01	0.04	3	0.1
KH17-2	SPW	59.43	1.36	38.71	0.22	0.21	0.06	0.00	0.01	0.13	0.3	0.02
KH17-3	SPW	59.35	1.47	38.50	0.32	0.24	0.13	0.00	0.01	0.14	0.5	0.09
KH17-4	KS	36.68	27.21	24.21	7.55	0.03	4.31	0.01	0.01	0.11	0.8	0.11
KH17-5	KS	44.85	0.31	22.30	9.41	0.01	0.06	0.00	0.03	0.09	0.5	0.15
KH17-6	MPW	60.28	0.16	39.00	0.15	0.02	0.02	0.00	0.01	0.15	0.1	0.13
KH17-7	KS	47.61	8.10	31.91	1.44	1.35	0.65	0.01	0.01	0.03	1	0.03
KH17-8	KS	40.33	7.71	19.14	9.73	0.03	1.38	0.00	0.03	0.09	3.3	0.04
KH17-9	NPW	54.14	3.81	35.40	0.77	0.52	0.45	0.01	0.01	0.02	1.2	-
KH17-10	NPW	60.45	0.12	39.18	0.06	0.04	0.01	0.00	0.01	0.18	0.2	0.09
KH17-11	NPW	60.16	0.29	38.94	0.13	0.10	0.08	0.00	0.01	0.07	0.09	0.05
KH17-12	NPW	45.65	6.73	30.43	1.30	1.18	0.49	0.01	0.01	0.03	5.1	0.12
KH17-13	TS	60.30	0.20	39.05	0.10	0.04	0.02	0.00	0.01	0.19	0.1	0.09
KH17-14	TS	49.69	12.67	31.31	3.80	0.02	2.50	0.00	0.02	0.14	3.2	0.1
KH17-15	TS	57.85	3.15	38.74	0.10	0.07	0.08	0.00	0.01	0.07	1.1	0.05
KH17-16	TS	58.63	2.21	38.62	0.27	0.25	0.02	0.00	0.01	0.10	1	0.06
KH17-17	MPW	60.49	0.18	39.21	0.05	0.02	0.04	0.00	0.02	0.18	0.2	0.04
KH17-18	MPW	58.27	2.69	38.02	0.55	0.19	0.28	0.00	0.01	0.12	1.2	0.11
KH17-19	MPW	60.19	0.52	39.09	0.10	0.07	0.03	0.00	0.01	0.10	0.1	0.03
KH17-20	MPW	53.49	0.40	31.01	2.29	0.02	1.35	0.00	0.01	0.07	2.6	0.06
KH17-21	S	49.30	12.68	37.90	0.04	0.02	0.06	0.00	0.02	0.15	3.3	0.03
KH17-23	S	59.67	1.11	39.03	0.08	0.05	0.05	0.00	0.01	0.13	1	0.07
KH17-22	S	60.22	0.47	39.04	0.14	0.08	0.04	0.00	0.01	0.08	0.5	0.09
KH17-24	B	59.69	1.13	39.03	0.04	0.01	0.11	0.00	0.01	0.12	0.7	0.1
KH17-25	B	59.37	1.54	38.56	0.16	0.11	0.25	0.00	0.01	0.12	0.9	-
KH17-26	NB	59.33	1.48	38.52	0.29	0.27	0.11	0.00	0.01	0.10	0.8	0.1
KH17-27	NB	56.31	4.83	36.54	0.20	0.13	0.05	0.00	0.01	0.03	1	0.08
K17-28	NB	54.08	7.42	38.26	0.05	0.01	0.18	0.00	0.02	0.15	1.1	0.08

SPW = south Pharwala; KS = Potash seam; MPW = middle Pharwala; NPW = north Pharwala; TS = Thin seam; S: =Sujowal; B = Buggy; NB = north Buggy.

Table 4. Details about the Warcha mine sequences and their corresponding thickness. Data are taken from Gee (1946) and Asrarullah (1963)

	Rock sequence in the Warcha	Thickness (m)
The salt	Gypsum, dolomite	-
range	Marl and thin seams of rock salt	-
formation	Rock salt	2-6
	Marl	1-2
	Rock salt	>4
	Marl	5-8
	Rock salt (main seams of NE)	>15
	Marl	8-10
	Rock salt (SW workings)	7-10
	Marl, Khallar and thin seams of salt	

Chemical characterization. Except for the Khallar seam, the halite purity from the Warcha deposit is up to 99%. Samples from the PMDC main mine are purer with a purity grade >99%. The maximum water insolubility is within the limit of 2.8%, coupled with the highest moisture content, around 0.15% (Hassan *et al*., 2016). Unlike the Khewra deposit, there is no exposed K^+ layer and the maximum K^+ concentration is ~1%. After NaCl, SO_4^{2-} is the main constituent with contents up to 2.63% (this study), whereas previous studies reported corresponding contents <1% (Hassan *et al*., 2016).

Kalabagh salt deposit. Kalabagh is the western end of the salt range, located near the Indus River (Fig. 1). Salt deposits in Kalabagh are relatively smaller and produce smaller amounts of salt that meet local demand.

Table 5. Ion composition (in wt.%) of rocks from the Warcha salt deposits

Sample	Cl^-	SO_4^{2-}	Br^-	NO^{3-}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Water insoluble	Moisture content
G-1	59.01	1.31	0.00	0.01	38.19	0.30	0.32	0.10	0.9	0.08
G-5	55.63	1.59	0.01	0.01	35.75	0.30	0.30	0.31	1	0.5
AZ-3	59.43	0.95	0.01	0.02	38.46	0.22	0.22	0.10	0.7	0.02
AZ-5	59.07	0.96	0.01	0.00	38.21	0.21	0.21	0.11	0.3	0.03
WS	59.50	0.54	0.00	0.02	38.53	0.14	0.05	0.07	0.2	0.02
WM	49.48	2.63	0.01	0.01	31.46	0.58	0.64	0.45	2.8	0.04
WC24-3	56.51	1.02	0.01	0.01	36.57	0.47	0.05	0.01	1.2	0.15
WC31-1	50.65	2.52	0.01	0.01	32.20	0.51	0.65	0.48	1.1	0.11
WC31-2	60.01	0.01	0.01	0.01	39.12	0.01	0.01	0.00	0.5	0.02
WC31-5	59.76	0.29	0.01	0.01	38.74	0.13	0.01	0.01	0.3	0.01
WC31-7	59.87	0.06	0.01	0.01	39.21	0.03	0.02	0.00	0.3	0.04

Table 6. Ion composition (in wt.%) of salt deposits in the Kalabagh area

Sample	Cl^-	SO_4^{2-}	Br^-	NO^{3-}	Na^+	Ca^{2+}	K^+	Mg^{2+}	Water insoluble	Moisture content
NC3-1	53.14	3.99	0.01	0.02	34.17	0.51	0.51	0.71	4.3	0.5
NC3-2	59.80	0.61	0.01	0.02	38.71	0.12	0.13	0.09	0.8	0.09
NC3-3	60.56	0.29	0.01	0.05	39.22	0.08	0.07	0.03	0.3	0.08
NC3-7	60.67	0.22	0.02	0.01	39.30	0.04	0.08	0.03	0.3	0.08
NC3-8	58.14	1.74	0.00	0.03	37.56	0.40	0.40	0.15	0.9	0.5
M2-1	60.06	0.26	0.00	0.01	38.94	0.04	0.04	0.04	0.2	0.03
M2-2	60.22	0.58	0.01	0.01	39.02	0.13	0.15	0.04	0.2	0.03
OC1-1	58.86	0.86	0.00	0.01	38.13	0.19	0.20	0.07	1.1	0.6
OC7-1	58.49	1.62	0.00	0.01	37.85	0.35	0.37	0.13	0.5	0.07
OC22-1	59.72	0.78	0.01	0.02	38.68	0.18	0.20	0.06	0.8	0.7
OC22-2	58.71	1.80	0.01	0.02	37.98	0.40	0.43	0.14	1.3	0.8
OC22-3	52.02	4.44	0.01	0.02	33.30	0.53	1.02	0.72	5.5	0.06

M2 and O = old mine; N = Drift 14.

Table 7. Ion composition (in wt. %) and water insoluble and moisture contents in salt deposits from the Kohat area

Sample	Cl^-	Ca^{2+}	K^+	Mg^+	Na^+	SO_4^{2-}	Water insoluble	Moisture content
A-1	59.110	0.270	0.010	0.002	38.306	0.590	0.6	0.05
A-2	59.260	0.220	0.011	0.002	38.410	0.460	0.5	0.02
A-3	55.030	0.920	0.011	0.002	35.616	2.050	2.3	0.15
B-1	59.960	0.009	0.012	0.002	39.045	0.023	0.9	0.07
B-2	55.880	0.850	0.019	0.004	36.171	1.900	3.1	0.16
B-3	55.810	0.830	0.016	0.006	36.125	1.870	4.1	0.09
C-1	54.550	0.980	0.016	0.003	35.266	2.110	4.3	0.08
C-2	56.550	0.660	0.013	0.001	36.775	1.790	2.1	0.04
C-3	58.240	0.480	0.011	0.013	37.731	1.100	1.1	0.03
D-1	47.350	0.980	0.018	0.006	30.586	2.110	6.1	0.15
D-1	52.670	1.040	0.051	0.013	34.105	2.470	3.2	0.12
D-2	54.010	1.150	0.015	0.003	34.917	2.520	3.5	0.09
D-3	49.630	1.300	0.017	0.003	32.102	2.960	3.9	0.04
E-1	55.840	0.910	0.014	0.001	36.160	2.050	2.9	0.07
E-2	56.190	0.680	0.012	0.001	36.392	1.510	2.1	0.03
~~E-3~~	~~55.060~~	~~1.100~~	~~0.013~~	~~0.001~~	~~35.529~~	~~2.270~~	~~1.9~~	~~0.08~~
M4-1	57.770	0.780	0.008	0.003	37.396	1.710	2.4	0.04
M4-2	56.440	0.880	0.008	0.004	36.562	2.030	5.2	0.6
M4-3	57.660	0.660	0.011	0.003	37.344	1.470	2	0.03
M17-1	57.540	0.780	0.010	0.003	37.228	1.700	1.9	0.12
M17-1	57.120	0.940	0.007	0.003	36.978	2.110	2.1	0.1
M17-2	53.200	0.870	0.017	0.004	34.422	1.920	4.1	0.05
M17-3	55.530	1.030	0.012	0.005	35.953	2.350	2.7	0.07
open Air	56.110	0.720	0.012	0.001	36.310	1.560	3.2	0.13

A, B and C = Jatta; D and E = Karrak; others are from Bahadurkhail.

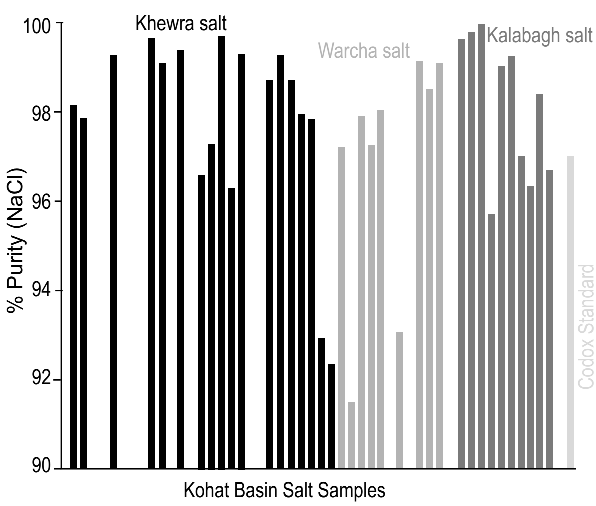

Fig. 6. Purity of the salt samples collected in the different mines of the salt range (expressed in % NaCl). The codex standard for purity in salts is reported for comparison. Samples with a purity <90% were discarded.

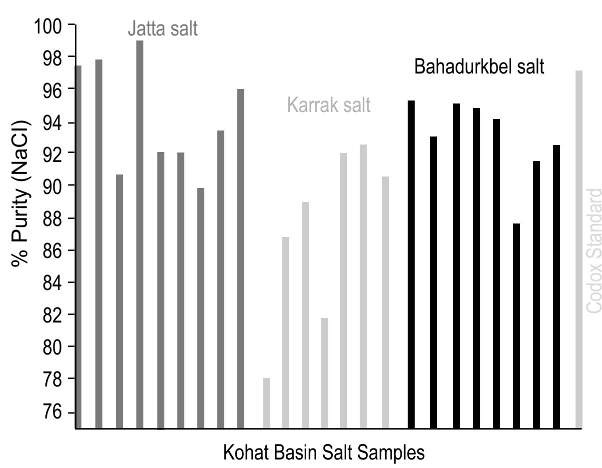

Fig. 7. Purity of the salt samples collected in the different mines of the Kohat basin (expressed in % NaCl). The codex standard for purity in salts is reported for comparison. Samples with a purity <75% were discarded.

Reserves and annual production. Due to its complex geological structure, a precise estimation of the salt reserves in the Kalabagh area is extremely difficult. However, the Salt Mines and Quarries Reorganization Committee roughly estimated the potential reserves at more than 1.10 million tons. Annual productions in 1946, 1961 and 2018 were 26,455, 17,636 and 142,540 tons, respectively (PMDC, 2019; Asrarullah, 1963).

Chemical characterization. Previous studies considered the salt from the Kalabagh deposits as the most impure among those of the salt range area (Asrarullah, 1963). In our study, the purity level ranges between 85 and 99%. Water-insoluble elements are similar to those reported for the other deposits within the SR area and reached a maximum of 5.5%. Moisture content vary from 0.07 to 0.8%. Again, after NaCl, SO_4^{2-} is the main constituent with content as high as 4.44% (Table 6), higher than reported by previous studies. Other major elements such as Ca, K, Mg are all = 1%.

The salt deposits of the Kohat-basin. ***Reserves and annual production.*** To date there is no exact estimation of the salt potential reserves of the KB. Still, the huge quantities already identified that extend over this large region indicate that sufficient salt reserves exist within the Kotab sub-basin. The Pakistan mineral development corporation recently roughly estimated reserves as over a few billion tons for each of the salt deposits (Jatta, Bahdurkhel and Karark salt mines) and a total of over 10.5 billion tons (Sharif *et al*., 2007) specifically for the Bahadurkhel salt deposits. The annual production for the sole Jatta salt deposit was 18,662 tons in 1870, under 38,000 tons in 1961, and 61,109 tons in 2018.

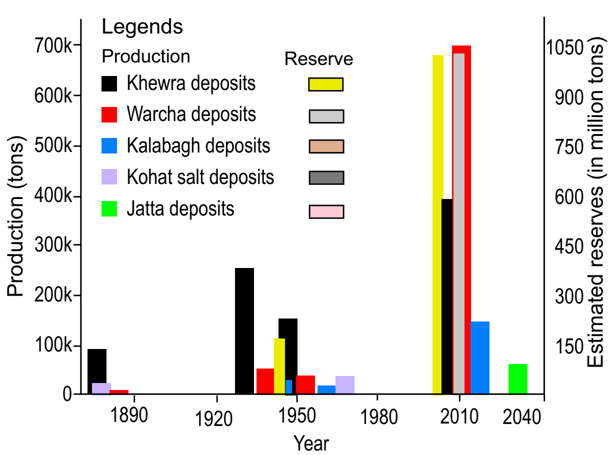

Fig. 8. Production and estimated reserves of the different Pakistan salt mines between 1870 and 2018. Data are taken from Table 2.

Chemical characterization. The Kohat basin's salts are greyish in color with impurities contents higher than those of the SR deposits. This greyish colour results from the intermixing of black bitumen/shale with rock salt, which in turn affects its purity.

Samples from the Jatta deposit (A, B and C) generally have a purity of about 95% with a moisture content around 0.16% and impurities varying from 1 to 4.3%. Samples from the Karrak deposit (D and E) display a lower purity (<95%). The insoluble matter is >6%. The purity level of the Bahadur Khel salt deposits is around 95% or lower with maximum impurities around 5.2% and a moisture content of 0.13%. All these results are consistent with the findings of Qadir *et al*. (2005) but distinct with those of Hassan *et al*. (2016) and PMDC (2019). These discrepancies are probably related to the sample selection and their respective locations. All other ions are <1%, except SO_4^{2-}, while the sulfate contents are the lowest in the Jatta deposits, they show similar values around 2.5% for the Karrak and Bahadurkhail salt deposits.

Conclusion

Rock salt is one of the major products of Pakistan and is considered as unexhausted in the subsurface of the salt range area. In this work, we discussed the rock salt reserves, geology, and annual production along with the chemical characterization of all Pakistan salt deposits. The main salt deposits are located in the upper Indus basin and spread over hundreds of km towards the Kohat-Potwar plateau. To date, identified salt reserves are estimated over 10 billion tons with a maximum production of 3,552,748 million tons in 2016, mainly originating from the Salt Range Formation. This production is still lower than its overall capacity and ranks 20th among the world salt producers. In this study, the halite of the Salt Range was found purer (99%) than the rest of the salt deposits in the Kohat basin. SO_4, present as an impurity, was generally =5% (wt.) and correlated with the K content in all deposits. All other elements (Mg, Li, B, NO_3 and B) were <1% with only Ca exceeding 1% in some K-rich samples. Based on their impurity contents our results suggest that the Kohat salts should not be used directly for human consumption.

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