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SALT LAKES ON THE INNER MONGOLIAN PLATEAU OF CHINA

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ABSTRACT: Salt lakes,the main source of trona resources in China, are widely distributed on the Inner Mongolian Plateau. Their characteristics are large in number, various in type, and short in salt–forming stage, especially their considerable number is well–known at home and abroad. The paper discusses the physical constituents, hydrochemical features, classification, formation, evolution, and salt–forming regularities of salt lakes through analyzing their distribution, lacustrine deposits and salt–forming conditions.

KEY WORDS: salt lakes, the Inner Mongolian Plateau

The Inner Mongolian Plateau is a large plateau in the northern part of China covering an area of about more than 1,400,000 km^2. Its west end begins from Alxa highland and the northern part of Ordos highland;its east terminal ends along Xilin Gol highland as well as Hulun Buir Basin. According to the investigation, there are about more than 220 salt lakes in the whole region, constituting a major part of salt lake zones in China. Influenced by dry climate,the process of formation of salt is strong,salt deposits develop well,especially there are a lot of alkali lakes, forming the main source of natron and trona in China. Probing and studying the basic characteristics and laws of formation and evolution of these salt lakes,it is of practical significance in revealing the features of natural environment on plateaus as well as the exploitation and utilization of the resources in salt lakes.

I. GENERAL DESCRIPTION OF SALT LAKES

1. Distribution of Salt Lakes

The salt lakes on the Inner Mongolian Plateau are located in the grasslands and the desert zone to the west of the Da Hinggan Mountains and the Luliang Mountains,north of the Loess Plateau and the Qilian Mountain,east of the Beishan Mountain,south of

Sino–Mongolia border. There exist many salt lakes in the region,but they are distributed unevenly and possess apparently regional and zonal features. Salt lakes occur in groups,forming four zones of salt lakes (Alxa, Ordos, Xilin Gol and Hulun Buir). As for the type of salt lakes, three zones(carbonate, sulfate and chloride types) are formed from southeast to northwest. Large salt lakes or groups of salt lakes are formed in regional structure basins,whereas groups of salt lakes are often formed in the margins of marshes and deserts. In the light of geological structure and physical geographical environment, four zones of salt lakes can be divided into (Table 1) [1,2]

Table 1 Main features of four salt lake regions in Inner Mongolia

Element	I Hulun Buir	II Xinlin Gol	III Ordos	IV Alxa
Structural units	Folded zones of Dahingganling–late Mongolian Hercynian movement		Ordos platform syncline	Alxa platform blocks
Geographical settings	Semi–arid grassland area	Arid desert grassland areas		Arid desert
States of neotectonics	Non–uniform lifting or falling		Large area rise	Large area rise
Formation of lake basin	Depressions of eroded river valley	Fault or depression basins	River–valley erosion and wind erosion depression	Wind erosion depressions in fault basin
Periods of formation of lake basins	late Quaternary	Late Tertiary to early Quaternary	Late Quaternery	late Tertiary to early Quaternery
Aridity coefficients	0.11	0.11—0.13	0.06—0.13	0.02—0.06
Types of ground water	HCO_3–Na	Mainly HCO_3–Na Locally SO_4–Na	HCO_3–Na (in east) SO_4–Na (in west)	SO_4– Na
Types of salt lakes	Sulfate type> Carbonate type		Carbonate type> Sulfate type> Chloride type	Sulfate type> Chloride type

Based on the classification principles of mineralized lakes proposed by Valyashko, M.G.,the salt lakes on the Inner Mongolian Plateau can be divided into three origin types of carbonate, sulfate and chloride. As the salt lakes are affected by geographical environment and hydrochemical factors, they have been formed into three obvious salt–forming zones which spread slightly in NE–SW direction(Fig.1), the main characteristics of each salt–forming zone are listed in Table 2.

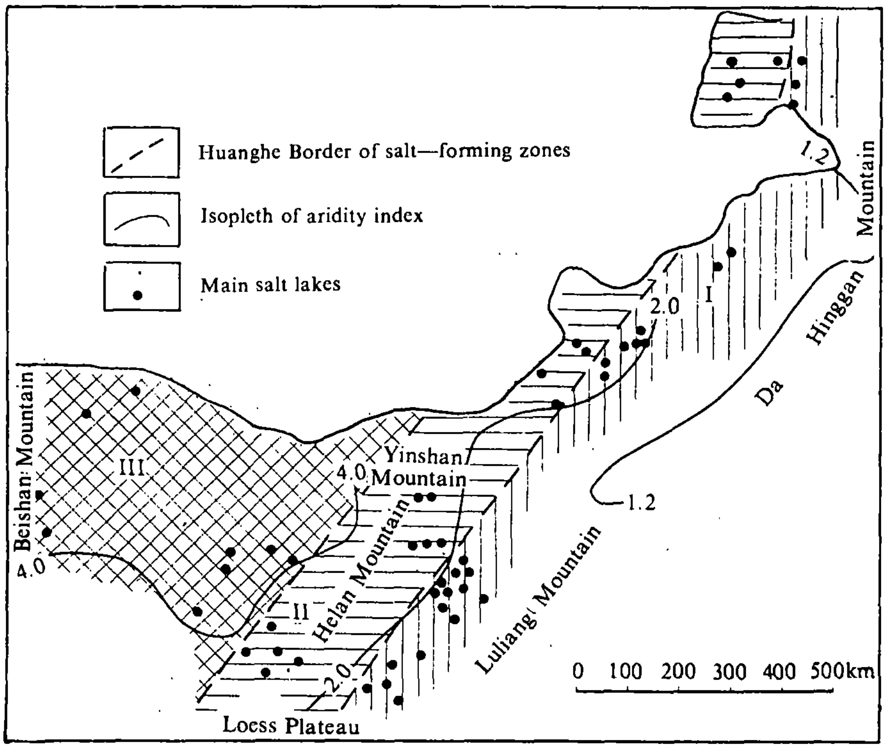

Fig.1 Distribution of salt–forming zones of salt lakes on the Inner Mongolian Plateau. Legend: I.Salt–forming zone of salt lakes of carbonate–sulfate type; II.Salt–forming zone of salt lakes of sulfate type; III.Salt–forming zone of salt lakes of chloride–sulfate type

Table 2 Salt–forming zones of salt lakes on the Inner Mongolian Plateau

Salt–forming zones	Salt–forming zones of carbonate–sulfate type of salt lakes	Salt–forming of sulfate type of salt lakes	Salt–forming zones of chloride–sulfate type
Natural environment	Arid grassland area	Arid desert and grassland area	Dry desert area
Hydrochemical types of ground water	HCO_3–Na	SO_4–Na	Cl–Na(Mg)
Aridity index	1.2—1.8	1.8—4.0	> 4.0
Major salt deposits	Natron,trona, mirabilite	Mirabilite	Mirabilite, halite
Typical salt lakes	Qaganlimen Nur Baiyan Nur Hatong Qagan Nur	Bayangchagang Eren Nur Yanhaizi lake	Jilantai, Yabrai salt pond

2. Chemical Compositions of Brine in Salt Lakes

There is little runoff at the margins of the salt lakes on the Inner Mongolian Plateau,the water supply to the salt lakes depends chiefly upon precipitation and ground water. Most of the salt lakes are often in semi–dry state except that there is surface brine in such salt lakes as Hatong Qagan Nur and Xijuyanhai (Gaxun Nur), etc. The brine in the region (surface brine and interstitial brine) is colourless, smellless and alkaline, tasting saline and bitter, its pH is 8—9. The salinity of lake brine is mostly more than 100 g / L, the highest 508 g / L (Qagan Nur). In accordance with the analysis, the brine in salt lakes on the plateau is mainly composed of Na, K, Ca, Cl, SO ,CO, HCO , making up 99.5% of the composition of ions in the brine (Table 3). Besides, the brine also contains a small amount of rare elements, such as Li,B, Br, etc.. Since their contents are low, they have not any great effect on the salt formation. However, they are locally enriched in individual salt lakes. For instance, the contents of B O in Baiyan Nur and Narin Nur are 965.4 mg / L and 804.5 mg / L respectively; while the contents of Br in Eren Nur and Beidachi are 300 mg / L and 68 mg / L respectively.

Table 3 The average component of brine in salt lakes on the Inner Mongolian Plateau

Salt lake types	Salinities (g / L)	mg / L				
		Na	K	Ca	Mg	Cl
Carbonate type	134.23	52082.03	2227.37	31.86	86.47	38300.67
Sulfate type	231.61	59903.93	7253.67	112.52	10323.49	97296.44
Chloride type	224.26	74582.21	4247.11	338.00	7511.21	137116.74

Salt lake types	Salinities (g / L)	mg / L				
		SO_4	CO_3	HCO_3	B_2O_3	LiCl
Carbonate type	134.23	5401.23	19992.26	22743.25	182.90	0.56
Sulfate type	231.61	48022.54	1373.73	2359.41	107.80	0.29
Chloride type	224.26	25.69	377.63	136.64	39.40	–

In terms of investigations and researches for many years,there are twelve minerals of evaporites(except silicate and aluminate minerals) in the salt lakes in Inner Mongolia,of which, five are carbonate minerals(natron, thermonatrite, trona, gaulussite and calcite); six are sulfate minerals (gypsum, thenardite, mirabilite, glauberite, hanksite and bloedite); one is chloride mineral (halite). The above–mentioned evaporites minerals have been accumulated in many salt lakes, constituting an important base of resources of trona, halite and mirabilite in China.

II. SALT LAKE DEPOSITS

1. Salt–forming Period

By analyzing the sections of lacustrine sediments,the salt formation of salt lakes on the Inner Mongolian Plateau took place chiefly in the Holocene(Q_4) of the late Quaternary, the salt–formation of individual salt lakes probably slightly earlier, beginning about the late stage of the Late Pleistocene (Q_3). Before that time,ie.in the Early and Middle Pleistocene (Q_1–Q_2) [3,4], the lakes were in their high lake level period. Though there were a great number of lake basins at that time, they did not possess favourable conditions for evaporation, because the climate was warm and humid. During the late stage of the Late Pleistocene to the early Holocene, dry and hot climate prevailed on the plateau,lake water retreated and became saline, and the deposits of evaporites started appearing in the northern part of the plateau. For example, there emerged evaporites of gypsum,mirabilite or trona, etc. in fault basins of Qaganlimen Nur, Naimandai, Eji Nur and Eren Nur on the Xilin Gol highland. From the data of cores, nine trona layers have been found in lacustrine sediments of more than 30m deep in Qaganlimen Nur, their accumulative thickness being 3—10m, the upper part has been dried and overlain by deposits of sand–bearing clay and clay. These deposits of salts might be the products of the earliest salt formation [5] since the salt lakes in the region evolved to the Quaternary.

In the late stage of the Holocene, dry climate was continuously dominating over the whole region, it was very windy and dusty,the lake levels retreated evidently and lake water was rapidly saline, the salt–formation appeared broadly on the plateau. The salt deposits of mirabilite, halite, trona, etc. developed extremely well, indicating that the salt lakes on the plateau had evolved into the second salt–forming stage. The salt–formation of this stage in the western part of the plateau developed better than that in the eastern part; for instance,the deposits of mirabilite and halite are 3—5 m thick in Zhongquanzi and Jilantai salt lakes on the Alxa highland; the sediments of mirabilite, halite and trona are approximately 1—2m thick in Yanhaizi, Hatong Qagan Nur in Ordos Basin; the deposits of mirabilite,halite in Eren Nur and Eji Nur on the Xilin Gol highland and sediments of mirabilite in Shaliboke and Baiyintaolimu salt lakes in Hulun Buir Basin are about 1—5 m thick. These salts are the deposits which were precipitated in the late Holocene,and are still precipitating at present,it is the most important salt–formation in the region (Fig.2).

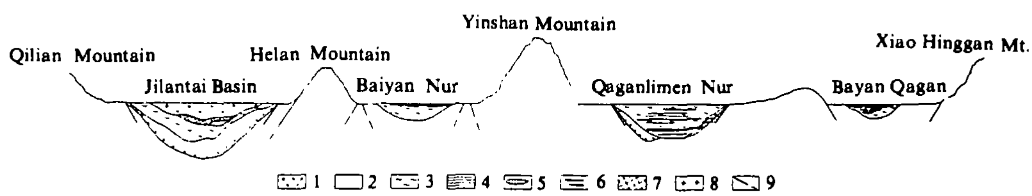

Fig.2 The section of evaporite deposits in the Late Pleistocene–Holocene Epoch.Legend: 1.conglomerate; 2.fine sand;3.mud; 4.mudstone; 5.gypsum; 6.trona; 7.mirabilite; 8.halite; 9.faults.

2. Lacustrine Sediments

According to the sequence,the salt lakes in Inner Mongolia can be divided into three types [2] : (1) clastic sediments composed of medium–and fine–sand; (2)clay deposits consisting of red—brown and dark—grey mud or salt—bearing mud;(3)deposits of evaporites formed by sodium and calcareous carbonates,sulfates and chlorides (Fig.3).

Lacustrine sediments are generally not very thick,all being within 50 m,salt deposits in them are mostly 1—2 m thick,10 m thick only in individual salt lakes. The deposits are commonly rather thick in the salt lakes which were formed in fault or depression basins. For example,the accumulative thickness of trona reaches 9.33 m in Qaganlimen Nur,whereas lacustrine sediments of some salt lakes formed in erosional depressions of ancient river valleys or in the erosional water—collecting depressions are usually about 6—8 m thick. The salt deposits in them are mostly about 1 m.

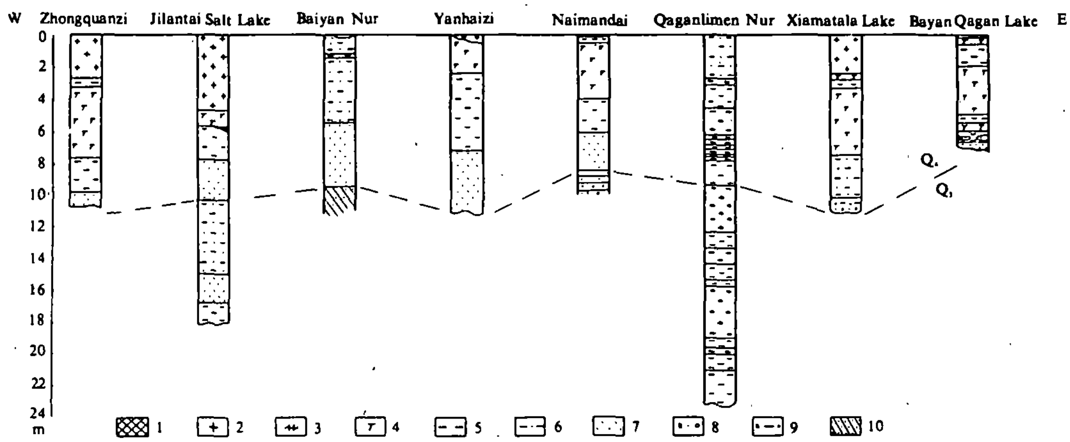

Fig.3 The correlation of precipitated sections of salt lakes on the Inner Mongolian Plateau (data from Inner Mongolian Geological Bureau,1963). Legend:1.gypsum;2.halite;3.trona;4.mirabilite;5.clay; 6.silty clay; 7.silt; 8.sand—conglomerate; 9.gravel—bearing clay; 10.sandstone.

The sequences of salt lake deposits in Inner Mongolia can be seen clearly and possess obvious rhythms [2], forming one sedimentary sequence—cycle beginning from clastic sediments to clay deposits and finally ending with the deposits of evaporites. This demonstrates a sedimentary environment that the climate varied from wet to dry,and neotectonics became from unrest to stable. Based on the number of cycles, tere occurred platform type of single cyclical sedimentation and geosyncline type of multicyclical sedimentation [1,2,5]. In platform type of single cyclical sedimentation,there emerged only one salt layer,for example,in the salt lakes in the syncline of Ordos and the platform block of Alxa. In geosyncline type of multicyclical sedimentation,new cycles appeared repeatedly overlying the first cycle,salt layers emerged many times,the maximum reaching twelve times,for instance in salt lakes in the folded zones of Dahingganling—Late Mongolian Hercynian movement.

The differentiation of salt deposits is the result of the formation and evolution of the salt lakes as well as the shifts of lacustrine sedimentary centres. Generally speaking,the phenomenon of differentiation of salt deposits is not apparent except few salt lakes

(Jilantai, Qaganchi, etc.) on the Inner Mongolian Plateau,this is an important indicator of salt–forming features of the salt lakes on the plateau.

There occur gypsum,mirabilite and halite from the lower part to the upper part in salt deposits in Jilantai salt lake;there precipitate gypsum,mirabilite and halite from the lake beach to the centre,the phenomenon of differentiation is obvious.

The phenomenon of differentiation is not so clear in other salt lakes, there principally exists one kind of salt mineral, forming a single salt deposit in most of the salt lakes, the rest salt minerals appear as associated minerals. For example, natron and trona deposits are dominant,but mirabilite or halite seldom in the salt lakes of carbonate type,while mirabilite or thenardite constitutes the major salt deposits,other minerals occur as the associated components in the salt lakes of sulfate type.

III. FORMATION AND EVOLUTION OF SALT LAKES

1. Forming Conditions of Salt Lakes

Dry climate,enclosed landform and rich source of salt constituents are the prerequisite conditions for the formation of potassium salt deposition,and also the basic factors for the salt–forming evolution of modern salt lakes. There is no doubt that the above–mentioned factors control each salt lake in different places inconsistently,some are primary and others are secondary,or vice versa because of the differences of geographical settings and structural conditions.

Generally,there are two types of salt lake basins in Inner Mongolia. One is depression or fault basins which are obviously controlled by structures,most of them spread in NE–SW direction, constituting the ideal places for large salt lake basins. The other is erosion river–valleys or wind–erosion depressions,their lake basins are shallow,flat and small,the former spreads regularly,the arranging direction usually accords with that of the ancient river–valley. For instance,lots of the salt lakes in the north of Ordos Basin and the southwest of Hulun Buir Basin were formed due to the erosion river–valleys and catchpits. The salt lake basins formed by wind erosion are changeable in shape and influenced greatly by wind and sand, even some have been buried by sand to become lakes underlying sand or buried lakes.

The aridity index increases gradually and climate becomes drier and drier from east to west,south to north on the Inner Mongolian Plateau(Fig.1). On the basis of the aridity index, two different climate regions of southeast and northwest are separated on the plateau, reflecting two entirely different physical geographical settings(Table 4).

From Fig.1 and Table 4, one can see that regional climate is evidently controlled and affected by landform,from east to west and south to north precipitation and relative humidity decrease gradually,while evaporation and air temperature increase apparently,and wind velocity becomes more rapid. The trend of progressive change illustrates that the climate in the northwest of the Inner Mongolian Plateau is drier than that in the southeast, it is much favourable for the formation of salt lakes.

Table 4 Various climatic characteristics on the Inner Mongolian Plateau

Elements	Northwest part	Southeast part
Aridity index	> 2.0	1.0—2.0
Precipitation(mm)	32.2—300.7	257.8—381.2
Evaporation(mm)	2171.1—3596.5	1270.6—1658.9
Evaporation / rainfall	15—30,max.60	3—8
Relative humidity	40—50	62—68
Mean temperature(℃)	5—9	3—1
Average wind velocity(m / s)	3.5—5.2	2.4—4.0
	Arid	Humid

The supply and shifts of salt elements are the material conditions for salt lake formation. The Inner Mongolian Plateau is situated in far inland and there is little runoff around salt lakes,thus cycles of ground water are the fundamental way to leach and dissolve the elements of salts in the rock formation and transport them.

The directions of the flowing of ground water in salt lakes exhibit obvious zonation,e.g. horizontal and vertical. As for horizontal zonation,it has two effective directions(Fig.4) which are from southeast to northwest and from the erosion source area of the

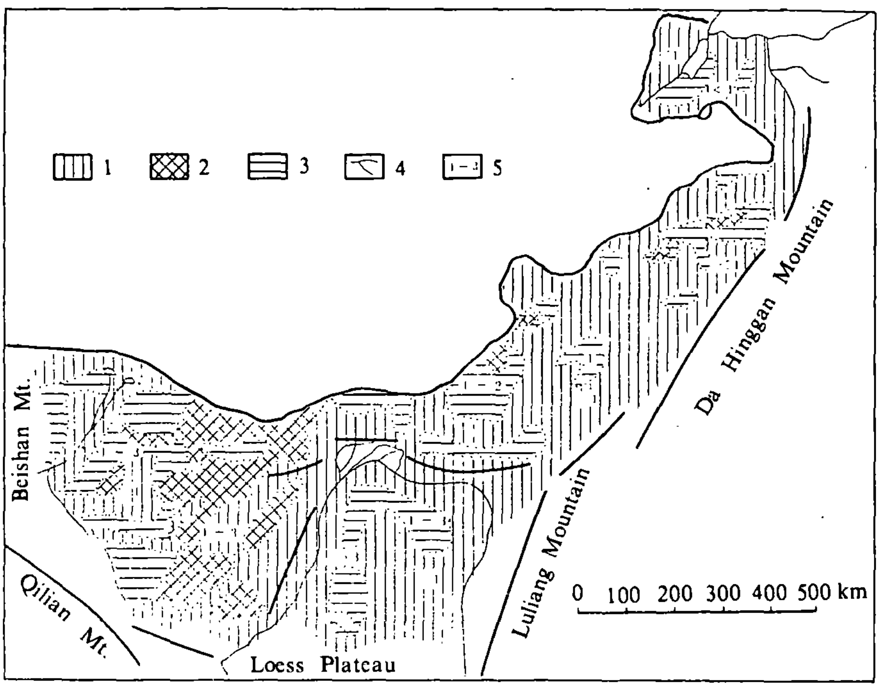

Fig.4 The hydrochemistry of ground water on the Inner Mongolian Plateau. Legend: 1.Carbonate type; 2.Sulfate type; 3.Chloride type; 4.Border of ground water type; 5.Salinity of ground water(g / L).

lake basins periphery to the concentrated region at the basin centres. From Fig.4, we can see that the types of ground water transit from carbonate and sulfate types gradually to chloride type with the strengthening of dry climate from southeast to northwest. The salinity of ground water also changes from less than 1 g / L and 1—3 g / L to more than 3 g / L. The directions of hydrochemical effect of ground water correspond to the distributing pattern from fresh water lakes, brackish lakes gradually transitting to salt lakes.

The change occurs from erosion source area,runoff region to the accumulated salt lake districts, and from the margins to the centre of the basin, namely, the salinities of ground water vary from less than 1 g / L, 1—3 g / L ,5—12 g / L finally to a brine of high salinity at the centre of the lake from the mountain area to the middle part of the lake in Jilantai Basin. The type of ground water evolves from HCO_3–Na and SO_4–Na types eventually to Cl–Na type(Fig.5). The phenomenon of zonation favors the leaching,dissolution and transportation of salt elements in rocks of erosion source area. In the light of the chemical analysis of the rocks in different periods in Ordos Basin in geological history, the periods favourable for salt–formation are Cambrian and Ordovician in the Paleozoic,the late Cretaceous in the Mesozoic, the Oligocene in the Cenozoic,and the Holocene(Fig.6) Among them the rock formation of the Paleozoic had little effect upon the salt lake regions for they are distributed surrounding the edges of the basins, while the rock formations of the rest periods played an important part in supplying salt elements and forming salt lakes,for they made up the basement of the salt lake basins. Generally,the salt lakes based on Huanhe,Luohandong and Jingchuan strata of the Cretaceous system belong to the salt lakes of carbonate type,whereas the salt lakes which spread in the salt–bearing rock systems of the Oligocene series in the Tertiary are mostly sulfate type. The geochemical background of salt–formation accords with the sources of salt–forming elements and the hydrochemical law of ground water in the region.

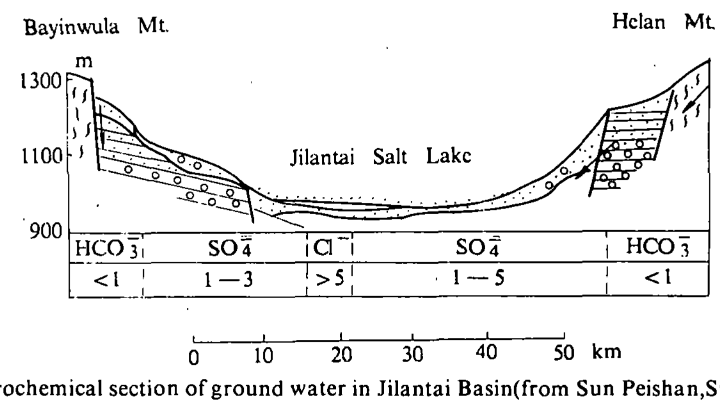

Fig.5 The hydrochemical section of ground water in Jilantai Basin(from Sun Peishan,Sun Deqin,1964)

The vertical zonation of ground water can be divided into normal and abnormal kinds. The normal zonation occurs mostly in the supplying area where drainage system develop well, the salinity of ground water increases with the depth of salt formation. The types of ground water change also with the increase of depth,for instance,HCO_3–Ca(Na) type on the surface is gradually replaced by SO_4–Na or Cl–Na type on the lower layer of

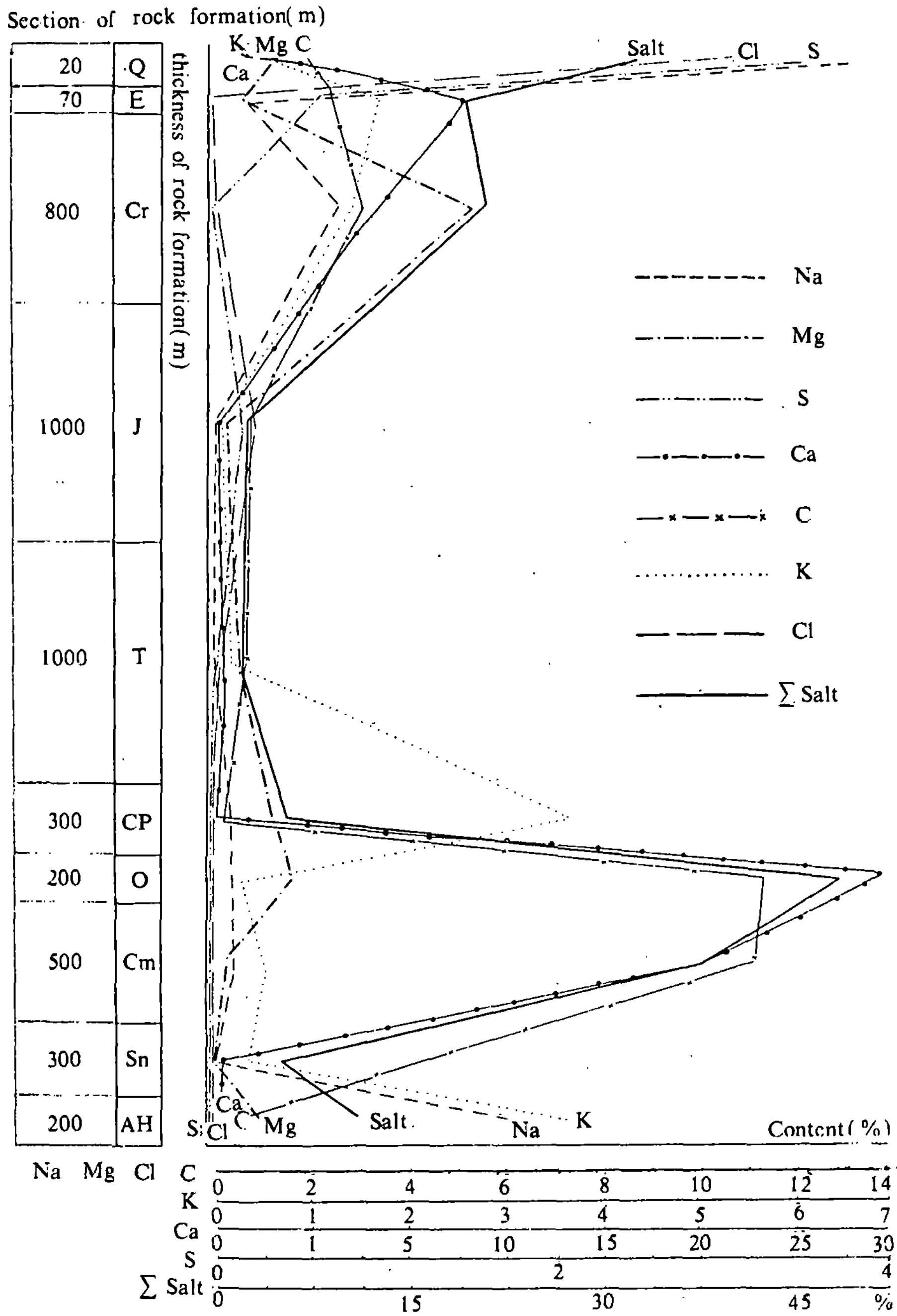

Fig.6 The section of salt–forming elements in Ordos Basin(from Guan Yukui,1963)

salt formation. The normal zonation is unfavourable to the formation of salt lakes,because the salt components are easily to be washed away and the salt–forming elements tend to become scattering. In the abnormal zonation, the salinity of ground water decreases with the increase of depth, e.g., it is less than 1 g / L in the deep bottom, while it reaches 3—5 g / L, even more than 50—100 g / L on the surface, for example, Jilantai, Eji Nur all belong to abnormal zonation. The concentration of ions is much enriched near the surface, especially Cl, Na, K, etc. In response to the hydrochemical types of ground water, HCO_3–Na type under ground is substituted by SO_4–Na or Cl–Na type, it is helpful for the formation of salt lakes and elements enrichment.

In short, the hydrochemical zonation of ground water not only reflects the law of the form and movement of ground water in erosion source areas, runoff regions to discharge districts, but also reveals the inevitable tendency of leaching, transportation and accumulation of salt. This is the geological and geographical background in controlling the formation and distribution of the salt lakes of carbonate, sulfate and chloride types from east to west and southeast to northwest on the plateau.

2. Evolution of Salt Lakes

The formation and evolution of salt lakes in Inner Mongolia exhibit the close origin relation to the differential rises and depressions between geosynclinal area and platform regions on the plateau. There occurred fault basins which were basically in accordance with the structure line in Xilin Gol district in the north of the plateau and Alxa area in the west of the plateau early in the Miocene and Pliocene. For instance, fault basins of Wenbunuoguole, Qaganlimen, Yabrai, Jilantai, etc. are the earliest ancient lake basins on the plateau. There existed clastic sediments of sand–conglomerate rock and mudstone, followed by gypsum, celestite etc., which were precipitated in dry climate environment [5]. At that time, the rise of large area of Hulun Buir and Ordos basins became local depressions (such as the southwest of Hulun Buir and the north of Ordos Basin). It did not become salt–forming conditions, because the climate was warm and rainy.

During the late Pliocene and the Middle Pleistocene, new depressions (such as Eren Nur) emerged one after another along the fault zones in the north of the plateau while the Himalayas movement began to be active and the original depressions became active and sagged continuously. Influenced by warm and humid climate, the fresh–water lake sediments such as sand and clay were deposited, showing that the lakes were in a period of high water levels [3,4].

During the late period of the Late Pleistocene to the early Holocene, the Inner Mongolian Plateau rose to a large extent, its regional climate was dry, desert and semi–desert, landscape developed well, some wind erosion, wide and shallow river valley depressions were formed, thus shallow lakes were formed. Affected by dry climate, some lake basins started possessing salt–forming conditions in the north of the plateau, there appeared evaporites deposits of trona and mirabilite, etc. in Qaganlimen Nur, Naimandai, Eren Nur respectively. In the middle Holocene, the temperature went up slightly again, the trend of lake water desalination became obvious, the deposits of sandy mudstone spread broadly in various lake areas.

In the late Holocene,climate became dry,lake water was strongly evaporated and highly concentrated and salt–formation was widespread on the plateau. Influenced by neotectonics and dry–humid climate, the sediments of interbedded salts and mud were produced in some salt lakes in the north of the plateau,whereas there was only one salt layer in the salt lakes in the south of the plateau,constituting a single lacustrine deposit. These salt lakes tend to be dry, and will eventually become playas, or lakes underlying sand.

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