Reservoir Volcanic Rocks: Geology and Geochemistry, the Mesozoic Non-marine Songliao Basin, NE China*

Pujun Wang[1], Zhiqiang Feng[2], Frank Mattern[3], Xuanlong Shan[1], Wanzhu Liu[1], Rihui Cheng[1], Chunguang Qiu[1], Huafeng Tang[1], Yan Zhang[1], Quanlin Li[1], Nuan Wen[1]

1. College of Earth Sciences, Jilin University, Changchun, 130026 China

2. Daqing Exploration & Development Institute, Daqing, 163712 China

3. College of Geology, Berlin Free University, Berlin, D-12249 Germany

Abstract The reservoir volcanic rocks in Songliao Basin include the Lower Cretaceous (K_{1yc} Form., 114~135 Ma, acidic rocks) and the Upper Jurassic (J_{3hs} Form., 145~158 Ma, intermediate rocks). Vesicles coupled with faults make the volcanic reservoir spaces which do not as badly getting worse with buried depth as those of sediments generally doing. The flood rhyolites of the Lower Cretaceous cover ca. 100 000 km^2 with relict thickness from 100 m to more than 1 000 m. They are high-silica, rich in aluminum and potassium, high REE contents with large negative Eu anomalies, thus believed also be formed by the large-scale sialic crust partial-melting. The andesitic rocks of the Upper Jurassic are rich in Al and K, but with lower REE contents and minor negative Eu anomalies, as well as dispersal patterns of HREE. They are believed to be produced by progressively shallower partial-melting where the fractionation of garnet and/or zircon may be involved. The most probable heat sources provided for the long-lasting volcanisms in the Songliao Basin is the subduction of the Okhotsk plate.

Key words reservoir volcanic rocks, Mesozoic, non-marine, Songliao Basin

1 Introduction

It has recently been recognized that most of the Ceno-Mesozoic sedimentary basins in eastern China contain volcanogenic and volcaniclastic successions developed especially in the early stages of the basin formation (Wang *et al.*, 1997; Cheng *et al.*, 1997; Chen *et al.*, 1999). These volcanic rocks can contribute to the oil/gas reservoirs under favorable condition (Wang *et al.*, 1997; Hu *et al.*, 1999). The characteristics of volcanism in the basins of eastern China can be compared to those of other regions in the northeastern Asia (Levin, 1995).

The first commercial oil reservoir of volcanic rocks in eastern China was developed in 1978 in the Huabei Oilfield (Tang *et al.*, 1988). The volcanic reservoirs in eastern China are generally deeply buried within the sedimentary basins (more than 3 000 m below the surface) and stratigraphically beneath the major sedimentary sequences. Because of the difficulties for their development, volcanic reservoirs had not been paid much attention until recent years when hydrocarbon exploration for the shallow parts of the basins had fundamentally been finished and the deeper parts hydrocarbon traps began to be the main targets. The research on volcanic reservoirs then evolved as a corollary of the exploration. More over, buried depth has less negative influence on the reservoir potential of volcanic rocks than on those of the sediments. This is a great advantage because one of the primary causes for economic failure within many of the Ceno-Mesozoic basins in

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eastern China is the limited reservoir potential within the lacustrine sequence of these basins (Katz and Liu, 1998).

Several high production natural gas pools had been discovered in the Mesozoic volcanic rocks from the northern portion of the Songliao Basin in early 1990's. It was then realized that the volcanism could not only create reservoir and cap rocks but also have some influence on the petroleum potential of the area, and provide insight into the nature of the evolution in the basin (Cheng *et al.*, 1997; shan *et al.*, 1999). Some authors believed that the deep seated faults associated with volcanism controlled the migration and accumulation of the non-biogenic natural gas in the Songliao Basin (Guo *et al.*, 1997; Dai *et al.*, 1996).

Recent studies on well-logging and seismic reflection allow tentative subsurface mapping and physical description for volcanic rocks in the Songliao Basin (Shao *et al.*, 1999; Yang *et al.*, 1999). However, in view of petrology, geochemistry and petrogenesis, the spatial and temporal association of the volcanic rocks in the basin had not been studied until 1997, which could provide important information for the further exploration and development of the volcanic reservoirs as well as for the research on basin evolution. In an attempt to understand the volcanism characteristics during the Mesozoic in the Songliao Basin, this paper examines the volcanic rocks in the Upper Jurassic Huoshiling Formation (J_{3hs}) and the Lower Cretaceous Yingcheng Formation (K_{1yc}) that occur in both core-sections and outcrops(Wang *et al.*, 1999). The paper presents the results of geological and geochemical investigation of these rocks and constrains their petrogenesis. Regional geological survey and stratigraphic correlation amongst the Songliao Basin and adjacent areas have been made by authors during recent three years (Wang *et al.*, 1999; Shan *et al.*, 1999; Song *et al.*, 1999). Isotopic dating on the volcanic rocks (Wang *et al.*, 2002a; 2002b) provides the basis for the results here.

2 Geological setting

The Songliao Basin is a tectonic controlled, volcanism associated, Mesozoic sedimentary basin (Liu *et al.*, 1993; Wang *et al.* 1997). It is today about 260000 km^2 and geographically restricted by surrounding mountain ranges. The basin is underlain by three fault slices of the Late Palaeozoic lower grade metamorphic rocks (slate, phyllite and carbonate), Hercynian granites and Precambrian crystallites (schiest and gneiss), and overlain by or in fault contact with clastic rocks of the Tertiary (0~500 m). Its basin succession is from Early Jurassic to Late Cretaceous. The volcanogenitic /pyroclastic rocks occurred mainly in the Upper Jurassic and Lower Cretaceous.

Deeply buried basement faults with predominant NNE trend define the geometry of the Songliao Basin, and somewhat the distribution of the volcanic rocks. The present eastern margin of the Songliao Basin is an eroded remnant confined by Jiayi fault zone. It is the northward extension of the famous Tanlu fault zone which is trans-through the whole eastern China. The basin's original boundary in the Cretaceous could be far more east to that of the present, because the Mid-Cretaceous deep lacustrine facies (Albian-Turonian) were recently recognized on the outcrops several tens kilometers eastward to the present edge during the regional geological survey by the authors.

3 Field relationship, petrology and mineralogy

The Lower Cretaceous Yingcheng Formation (K_{1yc}) is more important, in view of the volcanic reservoir, than the Upper Jurassic Huoshiling Formation (J_{3hs}), because it is more widely distributed

Left: vesicle and amygdale rhyolite; Right: silicified wood (in the middle)-containing clastic rocks with volcanic fragments

Fig. 1 Typical section of Lower Cretaceous Yingcheng Formation

and shallower buried. There are good lithostratigraphic correlation amongst sections both from boreholes and from outcrops. The whole volcanic series is a thick succession of lava flows, ignimbrites, volcanic breccias and ash flows, intercalating with alluvial /fluvial pyroclastic /clastic deposits. Typically, they consist of four well developed lithofacies which are, from bottom to top, lava flow facies, ignimbrites, pyroclastic rocks and tuffaceous deposits (Wang *et al.*, 2003a; 2003b). Each of those cycles measures several ten to more than a hundred meters. The lava flow facies are massive or have flow layering structures (often with fold patterns), associated with porphyritic, spherulitic and perlitic textures. Vesicles and amygdales filled with silica or fluorite are locally well developed in the rocks. The ignimbrites are massive or discontinuous lava flow beddings, and rich in embayed quartz and feldspar phenocrysts, typically with glassy unwelded or welded textures. The pyroclastic rocks are parallel to cross beddings (some times indistinct), associated with tuff structures consisting of crystals of quartz, alkali feldspar and plagioclase of various sizes and shapes, pieces of glass and/or rock fragments. The tuffaceous (normally transitional to epiclastic) sediments are apparently water transported, predominantly with poorly sorted but rounded volcanic clasts, deposited in the environments of alluvial fan and braided stream. Erosive contact exists between pyroclastic /tuffaceous deposits and underlain rock units which normally are thick massive to laminated fine tuffs, in many cases being composed of white illite and montmorillonite. An unequivocal unconformity contact between the early Cretaceous volcanic rocks (K_{1yc}) and Permian metamorphosed sediments (slates) was observed at an outcrop on the east margin of the basin. However, several kinds of contact between volcanic rocks and underlain strata, from high /low angular unconformity, parallel unconformity to conformity, were recognized within the basin based on seismic sections associated with core sections and well-logging (Yang *et al.*, 1999; Shao *et al.*, 1999). A group of shear faults, striking nor-northeast and nor-northwest, generally dipping steeply even vertically, were observed commonly both on the exposures around the basin and on the core-sections in the basin. The fault cracks coupled with vesicles in the volcanic rocks are the main reservoir space for the hydrocarbon migration and accumulation,and those reservoir qualities were very little affected by buried deepth, according to drilling results in the studied area. This is a great advantage compare to those of the normal clastic reservoirs. The average effective porosity of volcanic reservoir rocks for the studied wells are from 4% to 12%, but they are heterogeneous wildly.

The Lower Cretaceous Yingcheng Formation (K_{1yc}) are rhyolite and dacite dominant, and Upper Jurassic Huoshiling Formation (J_{3hs}) are andesite and trachyte dominant. The rhyolites are high-SiO_2 and Al_2O_3 rich (Wang *et al*., 2002a). The typical reservoir of volcanic rocks is low phenocryst porphyritic texture with complexity of phenocryst assemblage commonly including quartz, feldspars (sanidine, anorthoclase and plagioclase), biotite,hornblende, spinel(magnetite and ilmenite), and pyroxene. Typical section of the volcanic reservoir rocks is shown in Fig. 1.

4 Stratigraphy and vertical assemblage

Fig.2 shows the stratigraphic succession and vertical assemblage of the volcanogenic successions in the Songliao Basin. The basin filling sequence began with a coal-bearing siliciclastic deposits in the Early Jurassic(Hongqi Formation,J_{1hq}, in Fig.2). Fossils contained in the interbeds within the Upper Jurassic Huoshiling Formation (J_{3hs}) include *Ruffordia-Onychiopsis* flora early assemblge: *Nilssonia-Acanthopteris* assemblage; and pollen assemblage of *Aequitriadites-Cicatricosisporites-Protoconiferus*, suggesting Late Jurassic time according to the correlation with the adjacent area (Song *et al*., 1999) and consistent with the dated isotopic ages of 147 Ma~148 Ma (Wang *et al*., 2002a). The Lower Cretaceous Yingcheng Formation (K_{1yc}) is a thick volcanic and pyroclastic succession with intercalations of alluvial/ fluvial deposits (the right in Fig.1). Its thickness is more than 2 000 m in the outcrops exposed in the east of the Songliao Basin (Wang *et al*., 1999). The K_{1yc} began with rhyolite eruption at about 135~130 Ma, produced up to 1 000 m typically perlitic rhyolite and spherulitic rhyolite. The middle member of K_{1yc} is pyroclastic and clastic rocks containing coal seams and wood fossils (Fig.1), locally measuring 400 m thick. The upper part of K_{1yc} is composed of frequent finger-like interbedding of rhyolite - dacite - andesite - basaltic - trachyan desite-tephrite, with basic rocks dominant. The fossils contained in the sediment intercalations in the middle member of K_{1yc} Form. indicate Early Cretaceous in age (Song *et al*., 1999). The isotopic age data for K_{1yc} range from 135 Ma to 113 Ma (Wang *et al*., 2000a). The geological times in Fig.2 above the K_{1yc} are cited from Wang *et al*. (1996).

5 Geochemistry

5.1 Geochemiscal classification of major elements and series of the reservoir volcanic rocks

All the volcanic rocks of the Songliao Basin range from acidic to basic rocks (Tab.1). They are either peraluminous or metaluminous. On the average composition, all kind of volcanic rocks of the K_{1yc} Form. are peraluminous (A/CNK=1.09~1.66) except a few basaltic trachyandesites which are metaluminous (A/CNK=0.94, A/NK=2.18). The rhyolite and trachyte of the J_3hs Form. are peraluminous (A/CNK=1.16 and 1.02). Trachyandesite, andesite and basaltic trachyandesite of the J_3hs Form. are metaluminous (A/CNK=0.91,0.92,0.69 and A/NK=1.53, 1.77, 1.96). The series of the volcanic reservoir rocks of the Songliao Basin are almost all medium-K or high-K except a few of the J_3 hs Form. which are low-K.

5.2 Element distribution and association patterns of the volcanic reservoir rocks

Correlation analysis was done for every pair of the 53 major and trace elements listed in Fig.3. Seven element groups were classified based on the correlation results. From group 1 to group 6, all the elements have significantly positive correlation, and the concentration of one element can be expressed by that of any other element within the group with simple formula of y=kx+b. Group 7 is an exception, the element concentration of the group is totally in-

Stage	Formation	Stratigraphic Column	Lithic description	Fossil Assemblage	Age (Ma)
Cemomanian 99 Ma	K_1qt	—	Laminated multi-coloured pelite, siltstone, and sandstone	*Trilobosporites-Polyporopollenites*	94.0
Albian 112 Ma	K_1dl	—	Laminated dark colour pelite, siltstone, and sandstone	*Schizaeoisporites-Classopollis* *Leiotriletes-Polypodiaceaesporites* *Gleicheniidites-Clavatipollenites* *Cyathidites-Clavatipollenites*	102.0
Aptian 121 Ma Barremian 127 Ma	K_1yc	—	Light colour rhyolite, dacite, andesite, basaltic trachyandesite, tephrite; with interbedings of coarse classtic rocks	*Macxisporites, Verrutriletes, Trileites* *Ruffordia-Onychiopsis (late* sp.*)* *Piceites-Piceaepollenites*	113.0 120.0
Hauterivian 132 Ma Valanginian	K_1yc + K_1sh	—	Lateral alterations of K_1yc and K_1sh	*Granulatisporites-Lophotriletes* *Ricinospora leavigata*	130.0
137 Ma Berriasian 144 Ma	K_1sh	—	Dark colour siliciclasstic sediments and coal seam	*Classopollis-Osmundacidites* *Trileites sp.* *Macxisporites*	135.0
Tithonian 151 Ma Kimmeridgain 15 4Ma Oxfordian	J_3hs	—	Grey andesite, trachyandesite, basaltic trachyandesite, trachyte and rhyolite;with intercalations of fossil-bearing tuffites	*Aequitriradites-Cicatricosisporittes-Protoconiferus*	145.6 152.0
Calovian to Aalemian	J_2wb	—	Coal-bearing grey tuffaceous and/or siliciclastic sediments	*Coniopteris-Phoenicopsis (late* sp.*)*	158.0
Toarcian to Hettangian	J_1hq	—	Coal-bearing dark siliciclastic sediments	*Coniopteris-Phoenicopsis (early* sp.*)*	178.0
Pz and pre-Pz basement		—	Slate, phyllite, gneiss, granite, carbonate		208.0

Contacts: —— conformity; ------ parallel unconformity; ∿∿∿ angular unconformity

Fig. 2 Stratigraphic succession of Jurassic–Lower Cretaceous of Songliao Basin

(Time scale in the left column after Gradstein and Ogg, 1996)

Table 1 Typical chemical composition of the reservoir volcanic rocks of Songliao Basin

	Lower Cretaceous Yingcheng Formation (K_1yc)						Upper Jurassic Huoshiling Formation (J_3hs)				
Sample	RhK_1y	DaK_1y	$TraK_1y$	AnK_1y	BTK_1y	TeK_1y	$RhyJ_3h$	$TraJ_3h$	$TanJ_3h$	$AndJ_3h$	$BTaJ_3h$
SiO_2	77.0	66.3	63.4	59.8	53.25	47.22	75.5	65.82	61.68	59.48	52.66
CaO	0.49	1.34	1.06	1.3	6.1	0.97	1.05	1.69	3.9	4.47	8.18
MgO	0.51	2.98	4.58	4.4	2.74	3.41	0.62	2.44	2.99	3.42	3.79
Al_2O_3	11.5	13.3	16.31	14.7	18.47	13.94	11.19	15.2	16	15.61	15.98
P_2O_5	0.03	0.08	0.05	0.05	0.05	0.06	0.07	0.04	0.12	0.18	0.3
MnO_2	0.03	0.09	0.08	0.16	0.2	0.19	0.06	0.05	0.1	0.08	0.11
FeO	0.96	1.82	2.3	4.36	1.93	7.32	1.66	1.22	2.49	3.97	5.45
Fe_2O_3	0.93	4.16	1.49	2.86	5.46	3.54	0.68	1.89	1.62	1.69	1.35
TiO_2	0.15	0.75	0.56	1.2	1.56	3.06	0.27	0.44	0.61	0.74	1.08
Na_2O	3.02	2.7	4.5	2.57	4.1	5.62	1.8	5.16	4.65	4.66	3.93
K_2O	3.90	2.2	2.58	2.08	1.6	1.6	4.39	3.09	2.6	1.05	1.55
LOI	1.5	4.27	3.32	6.68	4.55	13.2	2.06	2.78	3.09	5.0	5.47
H_2O	0.10	0.0	0.0	0.0	0.0	0.0	0.71	0.0	0.47	1.05	0.37
A/CNK	1.14	1.43	1.35	1.66	0.94	1.09	1.16	1.02	0.91	0.92	0.69
La	51.9	49.5	25.7	37.5	38.1	42.25	55.26	22.03	23.46	14.72	23.31
Ce	105	105	52.1	71	70.9	84.54	92.86	40.55	41.98	28.66	43.81
Pr	11.68	11.5	5.22	8.8	7.4	9.23	11.25	3.67	4.66	4.61	7.55
Nd	43.6	43.9	20.8	36	28.7	46.45	47.66	17.64	18.78	14.9	23.4
Sm	9.25	9.43	3.96	8.8	6.37	9.08	8.35	2.68	3.43	3.09	4.97
Eu	0.27	0.73	0.98	2.0	1.56	1.96	0.44	0.68	0.87	0.79	1.13
Gd	7.19	7.24	2.46	6.12	4.47	6.16	6.64	1.84	2.29	2.43	3.4
Tb	1.28	1.2	0.34	1.0	0.69	0.57	1.09	0.24	0.37	0.59	1
Dy	7.58	6.96	2.12	5.7	3.99	6.32	6.43	1.66	1.92	1.96	2.95
Ho	1.50	1.3	0.39	1.1	0.74	0.96	1.42	0.26	0.36	0.52	0.8
Er	4.43	3.58	1.23	3.4	2.32	2.73	3.85	0.77	1.01	1.2	1.78
Tm	0.65	0.57	0.16	0.45	0.32	0.23	0.62	0.11	0.15	0.25	0.43
Yb	3.85	3.37	1.12	2.82	1.96	2.04	4.05	0.74	0.91	1.11	1.51
Lu	0.55	0.46	0.16	0.42	0.3	0.21	0.54	0.1	0.13	0.18	0.25
Y	40.0	38.7	12.4	30.7	20.7	33.48	35.65	8.98	10.25	11.27	16.24
Zr	472.6	561	123	270	150	220	460	170	165	155	245
Nb	37.9	40	10.0	24.5	14	45	44	10.2	12	9.8	20
As	5.12	2.7	4.2	3.87	7.5	243.3	11.5	3	9.9	9.6	3.4
Sb	0.62	0.35	0.35	0.24	0.26	1.5	0.35	0.2	0.33	0.3	0.32
Bi	0.3	0.27	0.16	0.17	0.22	0.15	0.17	0.17	0.13	0.11	0.13
Hg	0.11	0.1	0.041	0.05	0.017	0.172	0.02	0.08	0.1	0.04	0.024
Cu	30.7	17.7	24.0	36.2	44	30	21	22	25.8	36.5	62
Pb	25.5	27.7	20.5	14.6	17.5	16	21.5	18.8	28.3	8.5	8.9
Zn	73.6	83.7	47.5	81	77	83	73	42.5	58.8	65.5	60
Cr	9.58	10.1	15.0	97.3	77	8.9	27	62.5	166	185	250
Ni	7.11	11.5	17.0	51.4	39	6.4	13	36.25	76.3	62	81
Co	13.8	8.4	12.0	19.6	24	23	9.5	11.6	21.3	27.8	38
V	13.18	40.7	70.0	155	230	300	51	76.5	86	130	170
Sr	79.3	685	1050	195	740	230	225	600	840	645	870
Ba	171.7	855	920	283	530	280	780	1315	1075	495	620
Ge	0.2	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.4	0.75	0.6
Ga	3.75	0.0	0.0	0.0	0.0	0.0	21.5	0.0	9	20.5	17.5
Sn	5.03	3.8	1.0	2.17	1.5	2.3	2.8	1.25	1.55	1.2	2.2
In	0.02	0.0	0.0	0.0	0.0	0.0	0.08	0.0	0.03	0.08	0.07
Li	1.67	0.0	0.0	0.0	0.0	0.0	10	0.0	15.5	32	52
Be	2.54	2.7	1.4	1.8	1.2	1.1	4.1	1.05	1.7	1.6	1.9
B	17.4	15.3	10.0	17.7	15	10	13	11.4	13.3	18.5	14
Mo	2.13	1.0	1.4	1.23	20	2.1	0.5	2.75	1.4	0.9	2.4
Th	17.8	16	14.0	11.4	14.5	13.5	3	16.3	15.5	27.4	67
Sc	2.63	5.45	8.8	16	17.5	32	7.9	7.5	9.45	13.3	16

dependent with one another either within the group or with others. In addition, elements in the same group have similar geochemical characteristics in most cases. The Element distribution and association patterns of the volcanic reservoir rocks are shown in Fig.3. The explanation of each group and their preferable interpretation for petrogenesis are as follows:

Group 1: Si and K. They correlate positively with each other, but negatively or insignificantly correlatewith all the other elements in the volcanic rocks.

Group 2: Transitional elements (Sc, Ti, V, Cr, Mn, Fe, Co, Ni) and Mg as well as LOI (Los-On -Ignition which are mainly OH^- and F^- existing in hydrosilicates in this case). They are positive correlation and have simple concentration relationship with one another. Mg and LOI show very close affinity with the above transitional elements. They may have similar petrogenesis process (i.e. for the formation of the mafic hydrosilicates), so we put them in the same group in this study.

Group 3: Rare earth elements (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) and Y, Zr, Nb. They correlate positively and have simple concentration relationship with one another. But only Eu as well as Ce and Y (with minor importance) in the group shows concentration relationship with those of other groups. Because of their close affinity in concentration and similarity in geochemical character with REE, the three elements of Y, Zr and Nb were classified into this group. The noteworthy trait of this group is the positive correlation between Eu and Ca, Al, Sc, Ti, V, Mn, Fe, Mg and LOI respectively (in the linking boxes of Fig.3). They may indicate that Eu became a compatible element and began its main episode of crystallization during the lava evolution stage when such ferromagnesian silicates began to crystallize as diopside [Ca(Mg, Fe)$(SiO_2)_3$], hypersthene [(Mg, Fe)SiO_3], pyroxene [(Ca, Na)(Mg, Fe)Si_2O_6], hornblende [$NaCa_2(Mg, Fe)_4Al\text{-}Si_6Al_2O_{22}(OH, F)_2$] and biotite [$K(Mg, Fe)_3AlSi_3O_{10}(OH, F)_2$].

Group 4: Ca, Sr and Ba. They possess similar geochemical character and correlate positively with each other. The positive correlation between Ca and Eu suggests the co-crystallization and substitution of the two elements. The positive correlation between Ca and Sc,V,Co may indicate that the main episode of Ca crystallization occurred at the same time with those of transitional element. The maximum Ba content occurs at SiO_2=62% and there is a wild dispersal of Ba between SiO_2=57%-67%, suggesting its active change from incompatible to a highly compati-

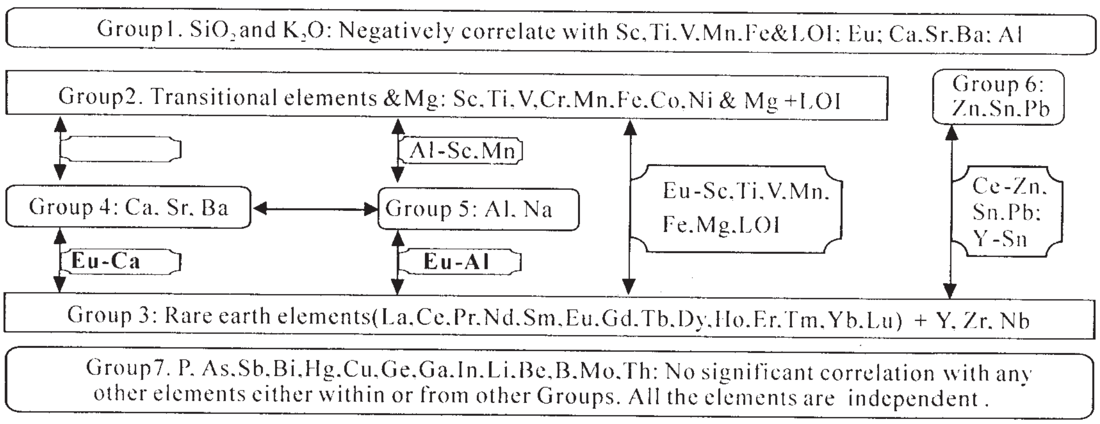

Fig. 3 Element correlation chart: summary of correlation results showing element distribution and association patterns in the reservoir volcanic rocks. Element pairs in the same "Group box" positively correlate. Elements in the connecting groups have inter-group correlation (see the text for detail)

ble element because of sanidine crystallization (Hess,1989), then Ba declines after SiO_2>70% suggesting its depletion in magma.

Group 5：Al and Na. In view of element correlation, Al and Na are unique. Na has no significant correlation with all other elements except Al. Aluminum has correlation with all other groups, but shows its affinity to only one or two elements of those groups. It has negative correlation with SiO_2 and K_2O of Group 1； positive correlation with Sc and Mn in Group 2, Eu and Sr in Group 4. The maximum Al_2O_3 occurs at SiO_2=51%, then it becomes negative correlation with SiO_2. This may indicate that there are two factors which control the concentration of Al in the volcanic rocks. One is aluminum source, the other is its distribution coefficient (K_D=Al-concentration in minerals /Al-concentration in melt, Brownlow, 1996). When SiO_2< 51%, it was $K_D$controlled aluminum crystallization. After SiO_2> 51%, aluminum abundance in the co-existing lava was the controlling factor, and the decline curve of Al_2O_3 with SiO_2 suggests an Al-depletion in the magma after SiO_2>51%.

Group 6：Zn, Sb, Pb. They are nearly an isolated group. The three elements have positive correlation with each other. But they have correlation only with Ce and Y from REE group and have no significant correlation with any other elements.

Group 7：P, As, Sb, Bi, Hg, Cu, Ge, Ga, In, Li, Be, B, Mo and Th. They have no significant correlation with any element neither within the group nor from other Groups. All the elements are concentration “independent”.

6 Conclusions

(1) The reservoir volcanic rocks in the Songliao Basin include the lower Cretaceous Yingcheng Formation (K_{1yc}) and the Upper Jurassic Huoshiling Formation (J_{3hs}). The former is composed of predominantly acidic rocks and the latter is intermediate rocks. The reservoir spaces for the volcanic rocks are the combination of primitive vesicles with fault crevices which are commonly found in eastern China as a group of high angle shear faults. The great advantage of the volcanic reservoirs is that their porosity and permeability do not as get worse with buried depth as those of sediments generally do.

(2) The flood rhyolites of the Lower Cretaceous Yingcheng Formation (K_{1yc}) cover ca. 100 000 km^2 with relict thickness from 100 m to> 1 000 m. They are high-silica, rich in aluminum and potassium, high REE contents with large negative Eu anomalies. They are believed to be formed by the large-scale sialic crust partial-melting. The melts were wet and fairly homogeneous.

(3) The intermediate volcanic rocks of the late Jurassic Huoshiling Formation (J_{3hs}) are Al and K rich, but with lower REE contents and minor negative Eu anomalies. They have dispersal patterns of HREE. They are believed to be produced by progressively shallower partial-melting where the fractionation of garnet and/or zircon may be involved, or formed by crystal fractionation of phenocryst phases from basalt, but with different extent of crust contamination.

(4) The most probable dynamics provided for the long-lasting volcanisms in the Songliao Basin is the continuous subduction of Okhotsk Plate under the North China Plate.

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