

Article

The Key Controlling Factors and Mechanisms for the Formation of Sandstone-Type Uranium Deposits in the Central Part of the Ulanqab Depression, Erlian Basin

Yang Liu ^{1,2}, Hu Peng ^{3,*} , Ning Luo ⁴, Xiaolin Yu ⁴, Ming Li ⁵ and Bo Ji ⁶

¹ School of Environmental Studies, China University of Geosciences, Wuhan 430074, China; 18066805503@163.com

² China Shaanxi Nuclear Industry Group Geological Survey Institute Co., Ltd., Xi'an 710100, China

³ School of Earth Sciences, Northeast Petroleum University, Daqing 163318, China

⁴ PetroChina Huabei Oilfield Company, Renqiu 062550, China; jhc_luon@petrochina.com.cn (N.L.); wtyyxl@petrochina.com.cn (X.Y.)

⁵ PetroChina Jilin Oilfield Company, Songyuan 138000, China; wty_lm@petrochina.com.cn

⁶ Xi'an Geological Survey Center of China Geological Survey, Xi'an 710100, China; jiboxa@126.com

* Correspondence: pengchuning@126.com

Abstract

The characteristics of interlayer oxidation zones constrain sandstone-type uranium mineralization. This study conducted a quantitative characterization of the interlayer oxidation zones in the uranium-bearing reservoir of the Saihan Formation in the central Wulanchabu Subbasin of the Erlian Basin through sand dispersion system mapping, the analysis of sedimentary debris components, environmentally sensitive parameters, and elemental geochemical characteristics. The formation mechanisms and controlling factors of interlayer oxidation zones were investigated, along with uranium mineralization patterns. Research findings reveal that the sandbodies in the study area primarily consist of red sandstone, yellow sandstone, gray ore-bearing sandstone, and primary gray sandstone, representing strong oxidation zones, weak oxidation zones, transitional zones, and reduction zones, respectively. Although the mineral debris content shows minimal variation among different zones, feldspar dissolution is more prevalent in oxidized zones. During interlayer oxidation, environmentally sensitive parameters exhibit an ascending trend from strong oxidation zones through weak oxidation zones and reduction zones to mineralized transitional zones. Four transition metal elements (Co, Ni, Zn, and Mo) demonstrate enrichment in mineralized transitional zones. The development of interlayer oxidation zones is directly controlled by reservoir heterogeneity and sedimentary environments. Oxidation subzones primarily occur in sandbodies with moderate thickness (40–80 m), sand content ratios of 40%–80%, and 2–10 or 10–18 mudstone barriers (approximately 20 m thick), mainly in braided river channels and channel margin deposits. Reduction zones develop in thicker sandbodies (~100 m) with higher sand contents (~80%), fewer mudstone barriers (2–8 layers), greater thickness (40–80 m), and predominantly channel margin deposits. Transitional zones mainly occur in braided distributary channels and floodplain deposits. When oxygen-bearing uranium fluids infiltrate reservoirs, oxygen reacts with reductants like organic matter, where Fe^{2+} oxidizes to Fe^{3+} , S^{2-} reacts with oxygen, and U^{4+} oxidizes to U^{6+} , migrating as uranyl complexes. As oxygen depletes, Fe^{3+} reduces to Fe^{2+} , combining with S^{2-} to form pyrite between mineral grains. Uranyl complexes reduce to precipitate as pitchblende, while some U^{4+} reacts with SiO_4^{4-} , forming coffinite, occurring as colloids around quartz debris or pyrite. The concurrent enrichment of certain transition metal elements occurs during this process.



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Keywords: Erlian Basin; Saihan Formation; sandstone-type uranium deposit; interlayer oxidation zone

1. Introduction

The formation of sandstone-type uranium deposits is influenced by various factors. The uranium mineralization processes in different basins exhibit diversity, but generally follow the redox and uranium valence change mechanisms. Meanwhile, these processes are largely controlled by a combination of key factors such as the uranium source, tectonics, the uranium reservoir spatial structure, interlayer oxidation zones, and the spatial distribution patterns of reducing media [1–12]. The interlayer oxidation zone can serve as a direct indicator for the exploration prediction of sandstone uranium deposits [1,7,13–15]. Interlayer oxidation zones are typically divided into oxidation zones, oxidation–reduction transition zones, and reduction zones, with uranium mineralization generally occurring in oxidation–reduction transition zones [16–20]. Consequently, investigating the key controlling factors and formation mechanisms of the interlayer oxidation zones is crucial for unraveling sandstone-type uranium metallogenic patterns and guiding exploration. Current global research on interlayer oxidation zones has advanced significantly, with most scholars characterizing the geochemical features of subzones from microscopic perspectives, while others have quantified the spatial distribution patterns of interlayer oxidation zones through integrated micro- and macro-scale approaches [21,22]. These studies emphasize that the developmental scale, internal architecture, and geometry of uranium reservoirs are pivotal factors controlling interlayer oxidation zone development [1,23–28].

In recent years, a series of uranium deposits, including Bayanwula, Saihangaobi, and Hada, have been discovered in the Saihan Formation of the Wulanchabu Depression, Erlian Basin, through collaborative efforts by the Nuclear Industry 208 Brigade, Tianjin Center of China Geological Survey, and North China Oilfield [29–32]. These deposits are controlled by phreatic-interlayer oxidation processes [33,34]. The sandstone-type uranium deposit in the study area is located in the eastern Naomugen Sag of the Wulanchabu Depression, southwest of the Hada uranium deposit. It primarily occurs in gray pebbly coarse sandstone within the upper member of the Upper Cretaceous Saihan Formation, exhibiting tabular orebody geometry. While previous studies on the Hada deposit have addressed stratigraphic subdivision, sedimentary environments of uranium reservoirs, oxidation zones, and metallogenic mechanisms [35–37], research in the study area has focused solely on uranium reservoir sedimentary environments, wide-field electromagnetic characteristics, and uranium occurrence modes [34]. This limited understanding of uranium mineralization mechanisms in the region has constrained subsequent exploration.

To address this gap, this study employs drilling core observation, clastic component analysis, sandbody mapping, and geochemical methods to investigate the characteristics of interlayer oxidation zones in the upper member of the Upper Cretaceous Saihan Formation in the Naomugen area of the Erlian Basin. We quantitatively characterize these oxidation zones and explore their controlling factors, formation mechanisms, and relationships with uranium mineralization.

2. Geological Setting

The Erlian Basin, situated in northeastern China, is a Mesozoic continental basin developed on the foundation of the Xingmeng–Hercynian fold belt [31,38–40]. It is bounded by the Great Khingan Mountains uplift to the east, the Ondor Sum uplift to the south, the Solon Mountains uplift to the west, and the Bayanbaolige uplift to the north. The

basin comprises five sub-basins and one uplift: the Chuanjing Depression, Wulanchabu Depression, Manite Depression, Tengger Depression, Unite Depression, and Sonid Uplift. The study area is located in the central Wulanchabu Depression (Figure 1a).

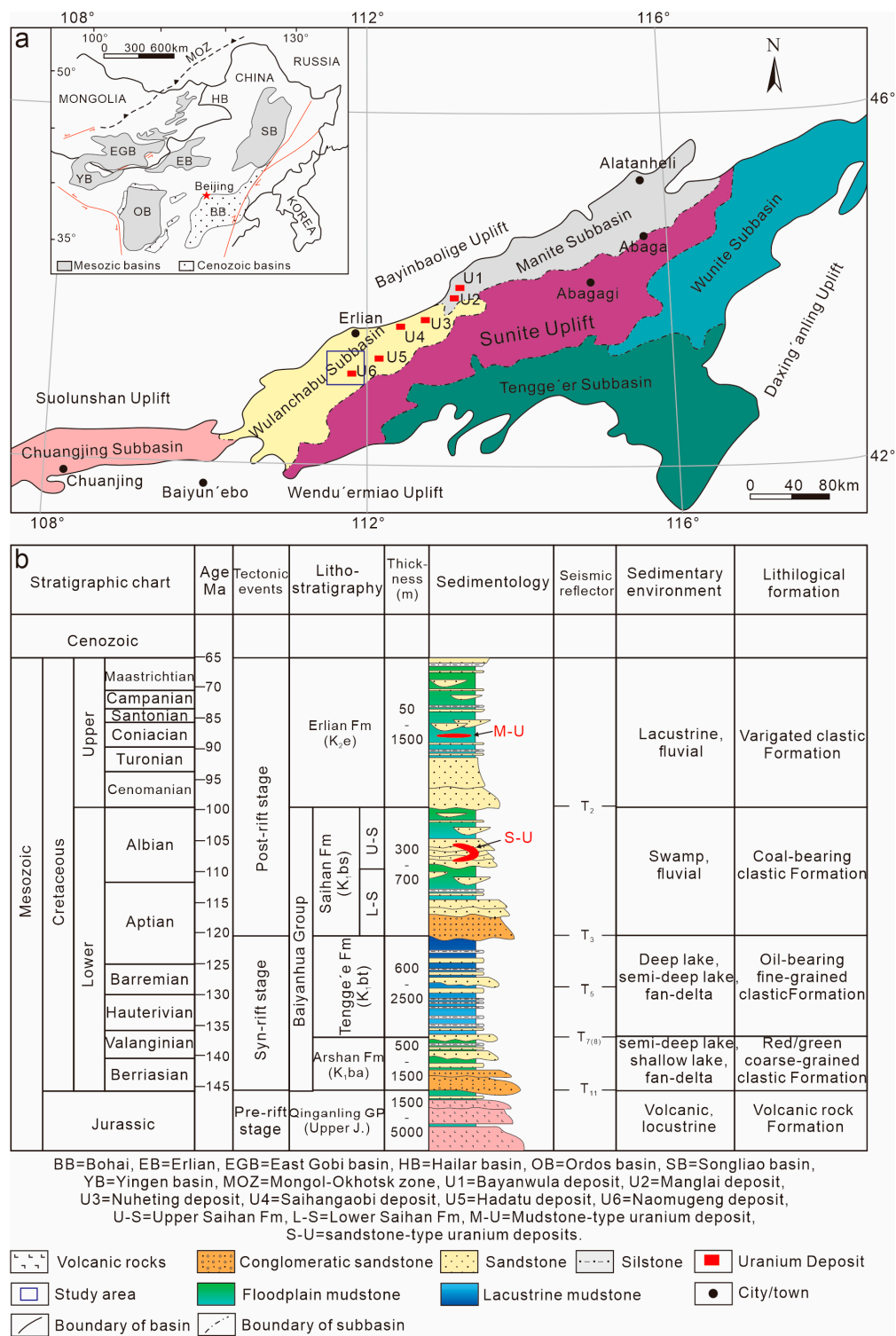


Figure 1. (a) Tectonic units in the Erlian Basin; (b) stratigraphic column of the Erlian Basin. Modified after Nie et al., 2020, Christophe et al., 2014 and 2015 [35,41,42].

The basin’s sedimentary fill sequence, from bottom to top, includes the following: the Alatanheli Group and Daxing’an Mountains Group, dominated by volcanic rocks intercalated with lacustrine and swamp sediments, coal-bearing coarse clastic deposits, and

alluvial fan deposits; the Arshan Formation, Tengger Formation, and Saihan Formation, characterized by fluvial, lacustrine, and deltaic facies deposits composed of mudstone, carbonate rocks, and sandstone; and the Erlian Formation, featuring variegated clastic deposits from fluvio-lacustrine and alluvial fan environments. The Erlian Formation primarily hosts mudstone-type uranium deposits, while the Saihan Formation contains sandstone-type uranium deposits, serving as the main ore-bearing horizon in the study area (Figure 1b) [35,41–45].

The Saihan Formation is divided into upper and lower members: lower members are composed of conglomerate, sandy conglomerate, grayish-black to black mudstone, with coal seams and shale, while upper members are dominated by gray to red conglomerate, sandy conglomerate, and variegated mudstone. The upper member of the Saihan Formation represents the primary host for sandstone-type uranium mineralization in the region [46,47].

3. Samples and Tests Methods

A total of 40 sandstone samples from the upper member of the Saihan Formation were collected from 16 boreholes in the study area. These samples underwent environmentally sensitive parameter analysis and petrogeochemical element analysis, all completed at the Nuclear Industry 203 Research Institute. Uranium (U) and total sulfur contents were determined using an ICPS-7510 inductively coupled plasma emission spectrometer manufactured by Shimadzu, Kyoto, Japan. Fe^{2+} , Fe^{3+} , and S^{2-} contents were measured with a Shimadzu UV-2600 UV-Vis spectrophotometer manufactured by Shimadzu, Kyoto, Japan. Organic carbon was analyzed using a LECO CS-230 carbon-sulfur analyzer manufactured by Laboratory Equipment Corporation in the Hayward, CA, USA. All tests achieved an accuracy better than 5%.

Major elements were analyzed with a PANalytical Axios X-ray fluorescence (XRF) spectrometer (Almelo, The Netherlands), with accuracy better than 5%. Trace elements and rare earth elements (REEs) were tested using inductively coupled plasma mass spectrometry (ICP-MS) (ELAN DRC II model) manufactured by PerkinElmer in the Springfield, IL, USA, achieving accuracy better than 5% and a relative standard deviation (RSD) of <5%. Detailed analytical methods are described in Wang et al. (2013) [48].

To observe the microstructure of sandstone and the occurrence forms of uranium, samples were impregnated with epoxy resin, and higher-grade samples were selected to prepare polished thin sections. The main procedures for sandstone slicing included sectioning, vacuum-assisted impregnation, grinding, mounting on slides, trimming, lapping, and polishing. Sandstone slice identification and uranium mineral composition/type identification by electron probe microanalysis (EPMA) were conducted at the Xi'an Center, China Geological Survey. Sandstone slicing was performed using a Nikon Eclipse LV100ND polarizing microscope manufactured by Nikon in Tokyo, Japan. Electron probe microanalysis (EPMA) employed a JXA-8230 (manufactured by JEOL in Tokyo, Japan) instrument with operating parameters set as follows: the electron beam voltage is 15 kV, the electron beam current is 10 nA, and the beam spot is 2 μm . Scanning electron microscopy (SEM) analysis utilized an FEI Nova Nano SEM450 manufactured by FEI Company in the Hillsboro, OR, USA field-emission scanning electron microscope with an accelerating voltage of 20 keV and a beam diameter < 1 μm .

4. Results

4.1. Macroscopic Identification of Interlayer Oxidation Zones

The sandstone of the Saihan Formation uranium reservoir can be classified into redox zones as follows: reduction zone—primary gray sandstone (Figure 2a); weak oxidation zone—yellow sandstone (Figure 2d); strong oxidation zone—red sandstone (Figure 2e);

and transition zone—sandstone exhibiting partial oxidation features, including locally oxidized gray sandstone with yellow patches (Figure 2b), gray sandstone oxidized to red but retaining residual gray areas (Figure 2c), and mineralized gray sandstone characterized by carbonaceous debris or streaks (Figure 2f).

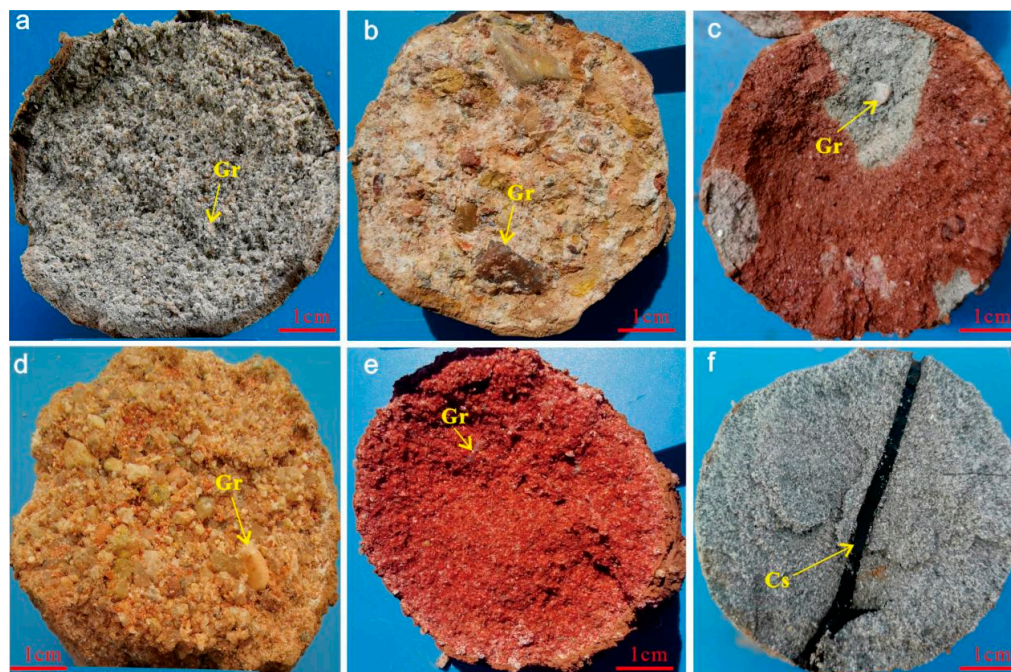


Figure 2. Epigenetic alteration of sandstones in the Saihan Formation. (a) Gray sandstone, 1–10, 618.1 m; (b) incomplete oxidation (yellow) sandstone, 1–1, 619.2 m; (c) incomplete oxidation (red) sandstone, 1–4, 632.1 m; (d) yellow sandstone, 1–15, 574.5; (e) red sandstone, 1–2, 598.9 m; (f) sandstone ore, 1–2, 613.5 m. Gr = gravel; Cs = carbonaceous strip.

4.2. Clastic Grain Characteristics of Interlayer Oxidation Zone

Petrographic analysis using polarizing microscopy and electron probe microanalysis (EPMA) revealed that the uranium reservoir sandstones exhibit a coarse-grained clastic texture with poor sorting. Grain sizes range from 0.08 to 4.5 mm, with point-to-line contacts between clasts and pore-contact cementation. Clastic components account for >90% of the rock, dominated by quartz (avg. 45%), followed by feldspar (avg. 18%) and lithic fragments (avg. 30%) (Figure 3a–f). The quartz was predominantly monocrystalline (90% of total quartz) and angular to subangular, with clean surfaces. Polycrystalline quartz, exhibiting cryptocrystalline textures and undulatory extinction, likely originates from metamorphic sources (Figure 3a–f). The feldspar was mainly plagioclase in tabular or short-prismatic forms, with minor potassium feldspar (Figure 3c–e). The lithic fragments were composed of igneous (dominant), high-grade metamorphic, and minor sedimentary (e.g., argillaceous) fragments (Figure 3a,b). Provenance discrimination reveals that all samples plot entirely within the arkose and lithic sandstone fields [49–53], indicating low maturity for the Saihan Formation sandstones (Figure 4a).

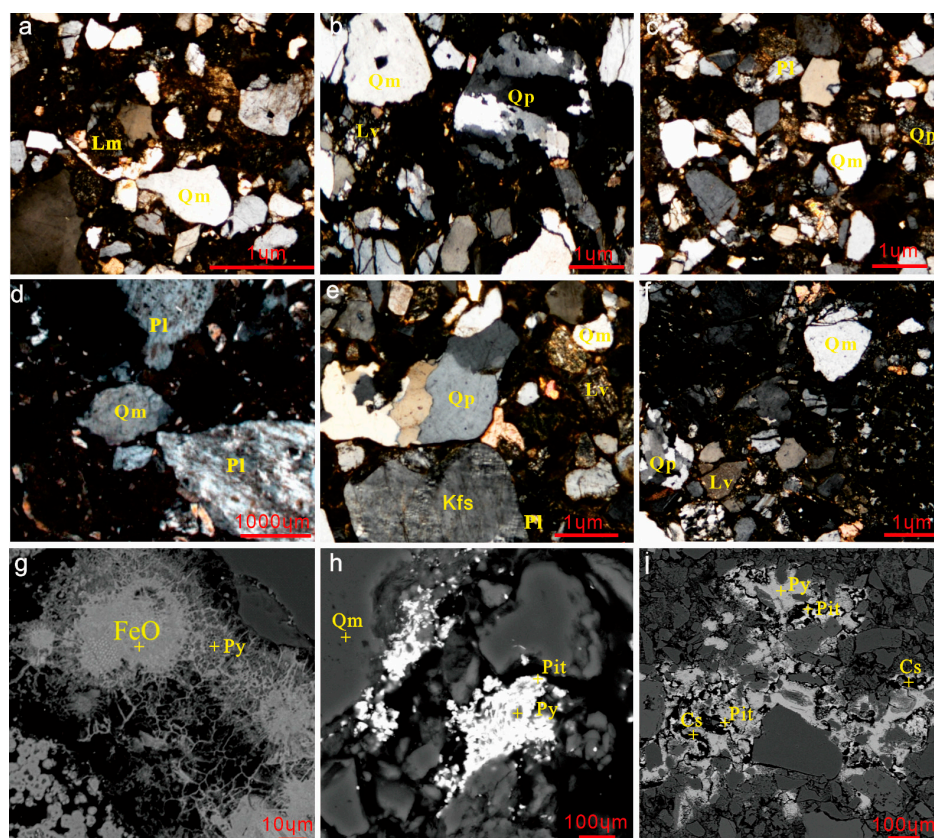


Figure 3. Micro-photos for sandstones from the Saihan Formation. (a) Metamorphic debris, monocrySTALLINE quartz, crossed polars, 1-20B5 Red Gritstone; (b) volcanic grains, monocrySTALLINE quartz, polycrySTALLINE quartz, crossed polars, NY1-4B3; (c) plagioclase, crossed polars, 1-3B1; (d) feldspar dissolution pore, crossed polars, 1-12B1 Red Gritstone; (e) K-feldspar, monocrySTALLINE quartz, polycrySTALLINE quartz, crossed polars, NY1-1B1 Yellow Gritstone; (f) monocrySTALLINE quartz, polycrySTALLINE quartz, 1-1B3 gray sandstone; (g) framboidal pyrite is oxidized, 1-13; (h) colloidal pyrite and pitchblende, 1-20TZ2; (i) colloidal pyrite, pitchblende, and carbonaceous strip 1-13TZ1. Qm = monocrySTALLINE quartz; Qp = polycrySTALLINE quartz; Kfs = K-feldspar; Pl = plagioclase; Lv = volcanic grains; Lm = metamorphic debris; Py = pyrite; Pit = pitchblende; Cd = carbon debris.

The strong oxidation zone exhibits a red pebbly coarse sandstone to sandy conglomerate, showing hematitization, composed of poor sorting, angular to subangular grains, with quartz (41% avg.), feldspar (30% avg.), and lithic fragments (18% avg.). Clast surfaces are coated with brownish material (Figure 3a,c,d), with frequent feldspar dissolution pores (Figure 3d) and oxidized pyrite, which iron oxides (Figure 3g). According to Figure 4a, except for one sandstone sample which is lithic sandstone, all other samples are arkose. The weak oxidation zone exhibits a yellow pebbly coarse sandstone to sandy conglomerate, displaying limonitization, alongside similar textural features to the strong oxidation zone, with quartz (42% avg.), feldspar (28% avg.), and lithic fragments (19% avg.). Feldspar dissolution is evident (Figure 3e). According to Figure 4a, four sandstone samples are lithic sandstone and six samples are arkose. The transition zone exhibits mineralized gray medium-to-coarse sandstone with carbonaceous debris, as well as moderately to poorly sorted, subangular grains, with quartz (45% avg.), feldspar (32% avg.), and lithic fragments (17% avg.). Pitchblende occurs between clasts and is closely associated with pyrite (Figure 3h,i), and it closely coexists with pyrite and carbon debris (Figure 3i). According to Figure 4a, there are two sandstone samples that are lithic sandstone and seven samples that are arkose. The reduction zone exhibits a gray medium-to-coarse pebbly sandstone or sandy conglomerate with carbonaceous debris, as well as moderately sorted, subangular grains, with quartz (50% avg.), feldspar (31% avg.), and lithic fragments (18% avg.). Min-

imal mineral dissolution is observed (Figure 3f). According to Figure 4a, there are three sandstone samples that are lithic sandstone and seven samples that are arkose.

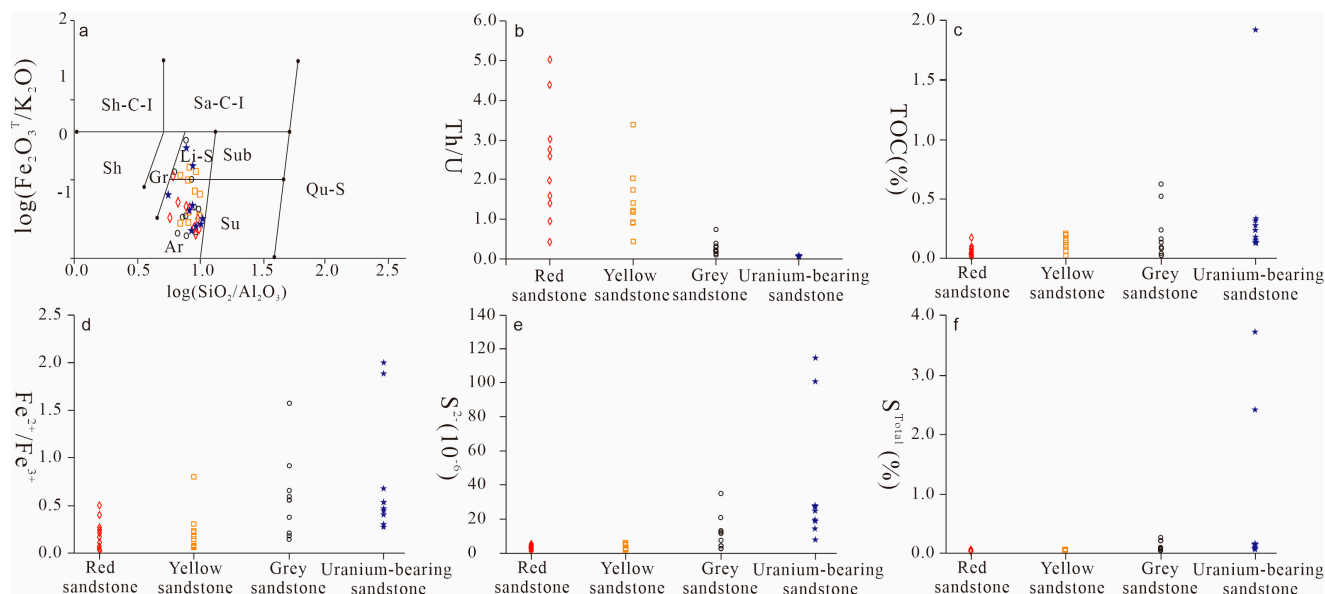


Figure 4. Characteristic map of environmental sensitive parameters in sandstone of the Saihan Formation uranium reservoir. (a) Log ($\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$)-log ($\text{SiO}_2/\text{Al}_2\text{O}_3$) discrimination diagram (after Herron, 1988 [52]), Sh-C-I = shale containing iron; Sa-C-I = sandstone containing iron; Sh = shale; Ar = arkose; Su = Subarkose; Li-S = lithic sandstone; Gr = Graywacke; Sub = Sublitharenite; Qu-S = quartz sandstone; (b) Th/U ratio characteristic map of Saihan Formation sandstone; (c) distribution map of organic carbon content in Saihan Formation sandstone; (d) distribution map of $\text{Fe}^{2+}/\text{Fe}^{3+}$ content in Saihan Formation sandstone; (e) distribution map of S^{2-} content in Saihan Formation sandstone; (f) distribution map of total sulfur content in Saihan Formation sandstone.

4.3. Environmentally Sensitive Parameters of Interlayer Oxidation Zones

4.3.1. Reduction Zone

The content of each element in the original gray sandstone of the reduction zone is as follows: The content of U is 8.42×10^{-6} – 47.80×10^{-6} (avg. 28.65×10^{-6}). The content of Th is 3.22×10^{-6} – 9.65×10^{-6} (avg. 6.22×10^{-6}). The content of Th/U is 0.09–0.74 (avg. 0.28). The content of organic carbon is 0.02–0.63% (avg. 0.19%). The content of $\text{Fe}^{2+}/\text{Fe}^{3+}$ is 0.15–1.58 (avg. 0.58). The content of S^{2-} is 2.58×10^{-6} – 35.10×10^{-6} (avg. 11.47×10^{-6}). The content of total sulfur is 0.02–0.25% (avg. 0.09%) (Table 1, Figure 4).

Table 1. The data of geochemical environmental characteristics of sandstone.

Sample Number	Lithology	Depth (m)	U (10^{-6})	Th (10^{-6})	Th/U	TOC (%)	Fe^{2+} (%)	Fe^{3+} (%)	$\text{Fe}^{2+}/\text{Fe}^{3+}$	S^{2-} (10^{-6})	S^{total} (%)
3-1-U3	Gray middle sandstone	713.34	10.70	3.22	0.30	0.24	0.22	0.39	0.56	7.62	0.06
3-1-U8	Gray coarse sandstone	714.64	19.20	6.34	0.33	0.16	0.25	0.38	0.66	11.90	0.07
3-U11	Gray glutenite	763.47	37.80	8.75	0.23	0.04	0.24	1.63	0.15	35.10	0.25
1-4-U1	Gray coarse sandstone	612.80	15.10	6.01	0.40	0.08	0.14	0.78	0.18	2.58	0.03
1-4-U3	Gray coarse sandstone	613.40	8.42	6.20	0.74	0.02	0.13	0.34	0.38	2.74	0.02
1-4-U7	Gray coarse sandstone	615.05	34.70	6.41	0.18	0.09	0.15	0.27	0.56	21.00	0.08

Table 1. Cont.

Sample Number	Lithology	Depth (m)	U (10 ^{−6})	Th (10 ^{−6})	Th/U	TOC (%)	Fe ²⁺ (%)	Fe ³⁺ (%)	Fe ²⁺ /Fe ³⁺	S ^{2−} (10 ^{−6})	S ^{total} (%)
1-4-U13	Gray coarse sandstone	619.03	38.60	5.21	0.13	0.13	0.13	0.61	0.21	4.35	0.04
1-20-U10	Gray coarse sandstone	611.30	28.80	5.99	0.21	0.02	0.14	0.24	0.60	4.11	0.02
1-15-U2	Gray fine sandstone	651.50	47.80	4.43	0.09	0.63	1.56	1.69	0.92	12.20	0.20
1-15-U4	Gray fine sandstone	652.35	45.40	9.65	0.21	0.52	2.07	1.31	1.58	13.10	0.20
3-1-U10	Red coarse sandstone	715.24	19.60	8.73	0.45	0.17	0.23	2.02	0.11	1.20	0.04
3-3-H2	Red coarse sandstone	686.85	1.24	6.20	5.00	0.05	0.06	0.28	0.21	5.00	0.01
1-2-H1	Red coarse sandstone	596.45	2.00	8.77	4.39	0.01	0.40	0.80	0.50	4.52	0.01
1-13-H4	Red coarse sandstone	620.25	2.00	5.54	2.77	0.02	0.12	1.66	0.07	3.00	0.05
1-20-H6	Red coarse sandstone	624.95	5.29	7.47	1.41	0.08	0.19	0.80	0.24	3.40	0.01
2-U5	Red fine sandstone	329.12	4.30	11.20	2.60	0.05	0.02	3.48	0.01	0.77	0.02
1-H1	Red fine sandstone	552.21	3.03	6.01	1.98	0.01	0.10	0.58	0.17	4.57	0.01
1-9-H3	Red coarse sandstone	615.55	1.00	3.02	3.02	0.03	0.08	2.30	0.03	4.68	0.01
1-11-H2	Red coarse sandstone	639.45	2.95	4.74	1.61	0.10	0.11	0.27	0.40	4.36	0.01
1-12-H2	Red coarse sandstone	635.25	6.36	6.12	0.96	0.07	0.13	0.49	0.27	3.20	0.01
3-1-U1	Yellow coarse sandstone	712.39	2.04	4.15	2.03	0.21	0.24	0.77	0.31	6.04	0.07
3-H2	Yellow coarse sandstone	654.15	1.24	4.20	3.39	0.01	0.12	1.73	0.07	0.86	0.02
4-H3	Yellow coarse sandstone	588.34	4.12	4.87	1.18	0.06	0.45	2.51	0.18	5.41	0.04
1-4-H3	Yellow fine sandstone	609.95	3.58	6.23	1.74	0.20	0.17	1.18	0.14	1.94	0.02
1-4-H6	Yellow coarse sandstone	623.95	1.34	1.59	1.19	0.15	0.16	2.52	0.06	2.90	0.01
1-20-H5	Yellow coarse sandstone	599.15	3.22	4.56	1.42	0.20	0.10	1.22	0.08	1.94	0.01
1-1-U12	Yellow coarse sandstone	617.45	4.54	4.22	0.93	0.09	0.22	2.86	0.08	5.72	0.05
3-2-H8	Yellow coarse sandstone	754.95	7.54	6.77	0.90	0.13	0.11	0.51	0.22	4.84	0.03
1-2-U2	Yellow fine sandstone	606.80	12.90	5.75	0.45	0.11	0.12	0.52	0.23	4.68	0.01
1-9-H4	Yellow coarse sandstone	625.05	3.79	4.57	1.21	0.11	0.28	0.35	0.80	5.08	0.01

Table 1. Cont.

Sample Number	Lithology	Depth (m)	U (10^{-6})	Th (10^{-6})	Th/U	TOC (%)	Fe ²⁺ (%)	Fe ³⁺ (%)	Fe ²⁺ /Fe ³⁺	S ^{2−} (10^{-6})	S ^{total} (%)
1-2-U6	Uranium ore body	609.05	397.00	4.21	0.01	0.13	0.54	0.27	2.00	24.60	0.16
1-2-U11	Uranium ore body	612.95	3210.00	7.12	0.00	1.92	0.56	2.05	0.27	101.00	2.42
1-2-U18	Uranium ore body	624.15	369.00	14.53	0.04	0.33	0.34	1.12	0.30	18.70	0.12
1-4-U14	Uranium ore body	633.30	952.00	7.48	0.01	0.17	0.32	0.47	0.68	7.42	0.05
1-13-U5	Uranium ore body	601.30	1380.00	6.00	0.00	0.15	0.12	0.22	0.54	14.20	0.17
1-13-U8	Uranium ore body	603.15	167.00	7.75	0.05	0.13	0.58	1.41	0.41	115.00	3.73
1-13-U15	Uranium ore body	607.50	758.00	7.86	0.01	0.23	0.20	0.44	0.45	28.00	0.16
1-20-U2	Uranium ore body	606.70	312.00	6.82	0.02	0.12	0.16	0.34	0.47	27.20	0.14
1-20-U4	Uranium ore body	607.55	173.00	8.94	0.05	0.31	0.16	0.30	0.53	27.70	0.16
1-20-U6	Uranium ore body	609.05	234.00	5.54	0.02	0.27	0.52	0.28	1.88	19.70	0.09

4.3.2. Strong Oxidation Zone

The content of U in strong oxidation zone is 1.0×10^{-6} – 19.60×10^{-6} (avg. 4.78×10^{-6}). The content of Th is 3.02×10^{-6} – 11.2×10^{-6} (avg. 6.78×10^{-6}). The content of Th/U is 0.45–5.0 (avg. 2.42). The content of organic carbon is 0.01–0.17% (avg. 0.06%). The content of Fe²⁺/Fe³⁺ is 0.01–0.5 (avg. 0.2). The content of S^{2−} is 0.77×10^{-6} – 5.0×10^{-6} (avg. 3.47×10^{-6}). The content of total sulfur is 0.01–0.05% (avg. 0.02%) (Table 1, Figure 4).

4.3.3. Weak Oxidation Zone

The content of U in weak oxidation zone is 1.24×10^{-6} – 12.9×10^{-6} (avg. 4.43×10^{-6}). The content of Th is 1.59×10^{-6} – 6.77×10^{-6} (avg. 4.69×10^{-6}). The content of Th/U is 0.45–3.39 (avg. 1.44). The content of organic carbon is 0.01–0.21% (avg. 0.13%). The content of 0.06–0.80 (avg. 0.22). The content of S^{2−} is 0.86×10^{-6} – 6.04×10^{-6} (avg. 3.94×10^{-6}). The content of total sulfur is 0.01–0.07% (avg. 0.03%) (Table 1, Figure 4).

4.3.4. Transition Zone

The content of U in weak oxidation zone is 167×10^{-6} – 3210×10^{-6} (avg. 795×10^{-6}). The content of Th is 4.21×10^{-6} – 14.53×10^{-6} (avg. 7.63×10^{-6}). The content of Th/U is 0.01–0.05 (avg. 0.02). The content of organic carbon is 0.12–1.92% (avg. 0.38%). The content of 0.27–2.0 (avg. 0.76). The content of S^{2−} is 7.42×10^{-6} – 115×10^{-6} (avg. 38.35×10^{-6}). The content of total sulfur is 0.05–3.73% (avg. 0.46%) (Table 1, Figure 4).

4.4. Geochemical Element Association Characteristics of Interlayer Oxidation Zones

The sandstone of the Saihan Formation uranium reservoir exhibits elevated contents of SiO₂ (avg. 78.12%), Al₂O₃ (avg. 9.61%), and K₂O (avg. 2.96%) among major elements, while MgO, TiO₂, and P₂O₅ show low concentrations (avg. < 1%). No significant differences in total major element contents or individual element concentrations are observed among sandstones of varying colors (Table 2).

Table 2. Results of major element analyses of sandstones from the Saihan Formation in the study area.

Sample Number	Lithology	Depth (m)	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ ^T	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	SO ₃	FeO	Fe ₂ O ₃	Loss
3-1-U3	Gray middle sandstone	713.34	77.33	0.18	10.03	1.01	0.09	0.61	1.05	1.66	2.99	0.02	0.13	0.28	0.70	4.42
3-1-U8	Gray coarse sandstone	714.64	76.38	0.19	10.45	1.05	0.08	0.59	1.06	1.82	3.23	0.02	0.14	0.32	0.69	4.88
3-U11	Gray glutenite	763.47	78.89	0.19	9.22	2.55	0.03	0.40	0.95	1.56	2.60	0.15	0.50	0.31	2.21	2.38
1-4-U1	Gray coarse sandstone	612.80	81.91	0.14	9.05	1.31	0.01	0.36	0.50	1.34	3.00	0.05	0.23	0.18	1.11	2.53
1-4-U3	Gray coarse sandstone	613.40	78.70	0.20	11.83	0.72	0.01	0.30	0.40	1.88	3.53	0.05	0.16	0.17	0.53	2.66
1-4-U7	Gray coarse sandstone	615.05	82.78	0.21	8.97	0.65	0.01	0.35	0.42	1.46	3.07	0.05	0.54	0.19	0.44	1.99
1-4-U13	Gray coarse sandstone	619.03	82.98	0.13	8.49	1.08	0.02	0.30	0.76	1.22	2.60	0.05	0.28	0.17	0.89	2.54
1-20-U10	Gray coarse sandstone	611.30	80.37	0.20	10.29	0.64	0.02	0.30	0.57	1.76	3.32	0.04	0.15	0.18	0.44	2.73
1-15-U2	Gray fine sandstone	651.50	68.46	0.14	8.84	8.58	1.32	0.31	0.59	1.25	2.81	0.10	1.27	5.87	2.06	6.65
1-15-U4	Gray fine sandstone	652.35	69.43	0.29	11.05	4.74	0.63	0.51	0.47	1.57	3.88	0.09	1.29	2.66	1.78	5.89
	MEAN		77.72	0.19	9.82	2.23	0.22	0.40	0.68	1.55	3.10	0.06	0.47	1.03	1.09	-
3-1-U10	Red coarse sandstone	715.24	66.18	0.28	11.40	3.18	0.03	0.77	0.88	2.59	3.03	0.07	6.32	0.96	2.11	5.18
3-3-H2	Red coarse sandstone	686.85	82.79	0.11	8.76	0.61	0.01	0.24	0.65	1.71	2.79	0.04	0.43	0.08	0.52	2.07
1-2-H1	Red coarse sandstone	596.45	78.80	0.12	9.52	1.34	0.03	0.61	0.79	1.76	3.13	0.06	0.38	0.14	1.18	3.45
1-13-H4	Red coarse sandstone	620.25	79.62	0.12	10.24	1.25	0.02	0.39	0.62	1.64	2.81	0.05	0.15	0.15	1.08	3.39
1-20-H6	Red coarse sandstone	624.95	77.35	0.20	11.57	1.44	0.02	0.40	0.67	1.64	2.85	0.06	0.15	0.24	1.17	3.83

Table 2. Cont.

Sample Number	Lithology	Depth (m)	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ ^T	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	SO ₃	FeO	Fe ₂ O ₃	Loss
2-U5	Red fine sandstone	329.12	76.73	0.27	13.38	1.03	0.02	0.36	0.67	1.67	3.20	0.05	0.15	0.44	0.54	3.20
1-H1	Red fine sandstone	552.21	82.01	0.12	9.07	0.78	0.01	0.26	0.57	1.54	3.22	0.04	0.01	0.13	0.64	1.87
1-9-H3	Red coarse sandstone	615.55	82.97	0.11	8.42	0.67	0.02	0.22	1.27	1.28	2.86	0.06	0.14	0.10	0.56	2.50
1-11-H2	Red coarse sandstone	639.45	81.68	0.10	8.85	0.62	0.03	0.25	1.42	1.46	3.11	0.04	0.07	0.14	0.46	2.75
1-12-H2	Red coarse sandstone	635.25	83.84	0.13	8.81	0.91	0.01	0.21	0.34	1.13	2.89	0.04	0.13	0.17	0.72	2.11
	MEAN		79.20	0.16	10.00	1.18	0.02	0.37	0.79	1.64	2.99	0.05	0.79	0.25	0.90	-
3-1-U1	Yellow coarse sandstone	712.39	79.45	0.19	9.90	1.03	0.02	0.22	0.84	1.46	2.75	0.06	2.14	0.80	0.14	2.56
3-H2	Yellow coarse sandstone	654.15	77.97	0.24	9.78	2.67	0.02	0.54	0.66	1.61	2.75	0.09	0.04	0.15	2.50	3.14
4-H3	Yellow coarse sandstone	588.34	74.15	0.26	10.65	3.93	0.02	0.53	0.36	1.95	3.70	0.06	0.11	0.19	3.72	3.59
1-4-H3	Yellow fine sandstone	609.95	81.44	0.15	8.20	1.87	0.02	0.34	1.25	1.28	2.93	0.06	0.15	0.22	1.63	2.76
1-4-H6	Yellow coarse sandstone	623.95	80.08	0.14	8.68	3.66	0.04	0.27	0.60	1.31	2.94	0.06	0.09	0.21	3.43	2.48
1-20-H5	Yellow coarse sandstone	599.15	76.17	0.10	8.38	1.89	0.08	0.13	4.57	1.31	2.72	0.05	0.11	0.13	1.75	4.94
1-1-U12	Yellow coarse sandstone	617.45	72.79	0.13	8.86	4.27	0.08	0.34	3.12	1.46	3.05	0.03	0.08	0.15	4.10	5.29
3-2-H8	Yellow coarse sandstone	754.95	77.58	0.20	11.13	0.95	0.01	0.43	0.59	2.16	3.43	0.05	0.24	0.14	0.79	3.04
1-2-U2	Yellow fine sandstone	606.80	79.72	0.15	9.85	0.95	0.01	0.06	0.79	1.79	3.41	0.05	0.13	0.15	0.78	2.91

Table 2. Cont.

Sample Number	Lithology	Depth (m)	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ ^T	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	SO ₃	FeO	Fe ₂ O ₃	Loss
1-9-H4	Yellow coarse sandstone	625.05	84.22	0.13	8.58	0.96	0.01	0.19	0.47	1.43	2.84	0.05	0.10	0.36	0.56	1.58
	MEAN		78.36	0.17	9.40	2.22	0.03	0.31	1.33	1.58	3.05	0.06	0.32	0.25	1.94	-
1-2-U6	Uranium ore body	609.05	81.84	0.11	9.05	0.68	0.02	0.04	1.08	1.31	2.87	0.04	1.01	0.10	0.57	2.31
1-2-U11	Uranium ore body	612.95	68.62	0.14	7.86	3.51	0.02	0.03	1.00	1.16	2.42	0.06	10.70	0.72	2.71	4.92
1-2-U18	Uranium ore body	624.15	69.43	0.70	14.06	2.03	0.03	0.13	0.94	1.81	2.96	0.10	0.88	0.44	1.54	6.54
1-4-U14	Uranium ore body	633.30	78.06	0.21	9.51	1.15	0.04	0.57	2.32	1.41	2.88	0.07	0.33	0.41	0.69	3.83
1-13-U5	Uranium ore body	601.30	83.00	0.12	8.01	0.67	0.02	0.18	0.46	1.23	2.55	0.05	1.29	0.15	0.50	1.79
1-13-U8	Uranium ore body	603.15	61.80	0.26	7.95	5.29	0.01	0.40	0.34	1.12	2.16	0.05	13.08	0.75	4.46	8.04
1-13-U15	Uranium ore body	607.50	80.66	0.23	9.26	1.08	0.02	0.21	0.38	1.76	2.33	0.06	1.23	0.26	0.79	2.66
1-20-U2	Uranium ore body	606.70	83.99	0.23	7.88	0.82	0.02	0.25	0.56	1.19	2.72	0.04	0.88	0.21	0.59	2.09
1-20-U4	Uranium ore body	607.55	82.36	0.23	8.93	0.75	0.01	0.27	0.43	1.39	2.98	0.04	1.01	0.21	0.52	2.17
1-20-U6	Uranium ore body	609.05	82.12	0.14	9.64	0.66	0.01	0.22	0.57	1.33	2.95	0.05	0.53	0.15	0.49	2.35
	MEAN		77.19	0.24	9.22	1.66	0.02	0.23	0.81	1.37	2.68	0.06	3.09	0.34	1.29	-

Trace elements in the uranium reservoir sandstones display high average concentrations of Ba (560.74×10^{-6}), Sr (163.19×10^{-6}), Rb (98.74×10^{-6}), and V (83.06×10^{-6}), with other elements ranging between 1.98×10^{-6} and 67.18×10^{-6} . Notably, transition metal elements Co (31.20×10^{-6} avg.), Ni (25.25×10^{-6} avg.), Zn (51.14×10^{-6} avg.), and Mo (24.86×10^{-6} avg.) are enriched in terms of the total REE content or individual element compared to other subzones (Table 3, Figure 5a).

Rare earth elements (REEs) in the sandstones show elevated average concentrations of Ce (48.30×10^{-6}), La (25.13×10^{-6}), and Nd (20.13×10^{-6}), with other REEs ranging from 0.20×10^{-6} to 5.71×10^{-6} . All samples exhibit consistent REE distribution patterns (Figure 5b), characterized by right-leaning profiles with flat heavy REE (HREE) curves, suggesting similar provenance and tectonic settings across oxidation subzones [54,55]. No significant depletion or enrichment in the total REE content or individual element concentrations is observed among subzones (Table 4).

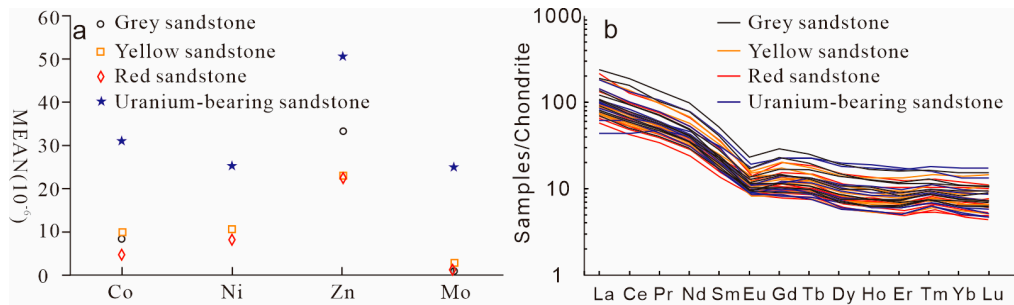


Figure 5. Elemental geochemical characteristics of Saihan Formation sandstone. (a) characteristics of trace element content in Saihan Formation sandstone; (b) REE standardized partition curve of chondrites (after Taylor et al., 1985 [56]).

The results demonstrate minimal variation in mineral clast content across zones, though feldspar dissolution is more prevalent in oxidized zones. During interlayer oxidation, environmentally sensitive parameters increase progressively from strong oxidation zones through weak oxidation and reduction zones to mineralized transitional zones. Transition metal elements are notably enriched in the mineralized transitional zone (Figure 6).

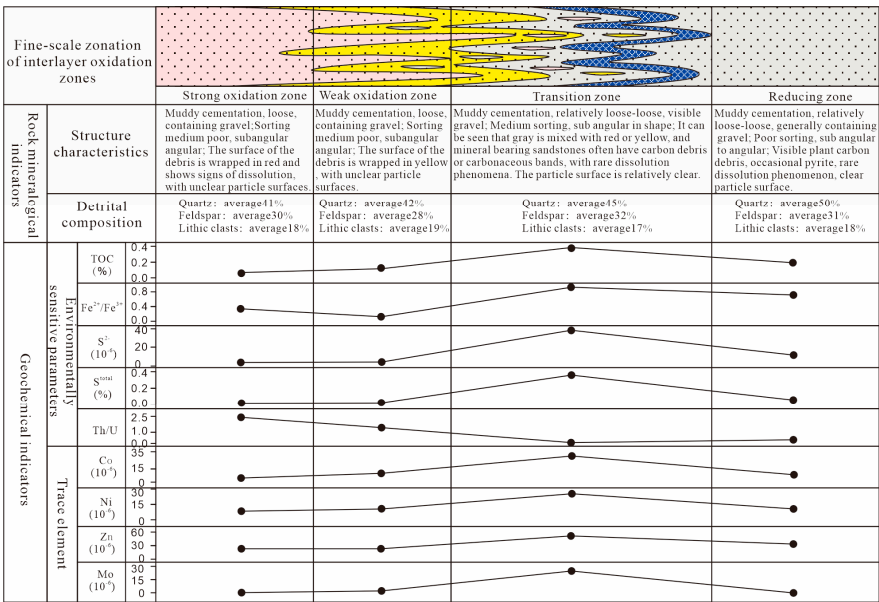


Figure 6. Model of architecture of the interlayer oxidation zone in Saihan Formation of the research area.

Table 3. Results of trace element analyses of sandstones from the Saihan Formation in the study area.

Sample Number	Lithology	Depth (m)	Rb	Ba	Sr	Zr	Hf	Y	Pb	Sc	V	Cr	Cu	Co	Ni	Zn	Mo
3-1-U3	Gray middle sandstone	713.34	88.50	564.20	138.20	47.10	1.46	10.96	17.00	2.72	48.80	9.65	4.26	3.18	7.06	20.00	0.33
3-1-U8	Gray coarse sandstone	714.64	109.00	529.90	166.50	77.10	2.30	15.30	15.70	3.71	72.50	14.60	68.00	4.77	8.90	26.70	0.35
3-U11	Gray glutenite	763.47	101.00	439.90	111.10	118.00	3.09	14.70	14.20	8.71	79.60	38.10	22.10	6.75	20.50	56.50	0.26
1-4-U1	Gray coarse sandstone	612.80	97.70	589.10	130.90	76.30	2.08	21.70	15.90	3.33	97.50	13.00	7.80	2.59	6.33	22.00	0.93
1-4-U3	Gray coarse sandstone	613.40	136.00	573.20	153.20	83.80	2.48	11.80	20.00	3.60	130.80	10.00	7.67	11.10	6.58	27.10	0.50
1-4-U7	Gray coarse sandstone	615.05	106.00	468.90	124.00	68.50	2.14	11.90	24.70	3.15	58.20	13.60	6.25	23.10	8.30	22.70	0.58
1-4-U13	Gray coarse sandstone	619.03	84.90	577.80	150.60	47.10	1.39	10.60	13.50	3.44	41.30	13.30	7.63	6.02	8.40	39.10	0.49
1-20-U10	Gray coarse sandstone	611.30	115.00	514.80	144.10	61.60	1.88	10.40	12.80	3.28	108.20	10.50	7.48	4.46	8.50	28.20	0.24
1-15-U2	Gray fine sandstone	651.50	104.00	446.60	109.20	59.90	1.84	19.90	15.30	4.10	23.20	39.80	5.52	12.60	17.90	30.00	1.30
1-15-U4	Gray fine sandstone	652.35	155.00	453.80	109.80	130.00	3.12	28.00	19.40	6.12	30.80	23.80	6.22	9.88	12.80	60.90	1.10
	MEAN		109.71	515.82	133.76	76.94	2.18	15.53	16.85	4.22	69.09	18.64	14.29	8.45	10.53	33.32	0.61
3-1-U10	Red coarse sandstone	715.24	124.00	690.40	168.20	138.00	3.81	20.70	31.70	6.09	49.00	26.00	7.89	22.50	30.10	42.20	4.50
3-3-H2	Red coarse sandstone	686.85	85.00	724.70	207.00	36.00	1.01	8.08	14.70	2.36	15.20	8.00	4.41	1.43	4.22	14.20	0.34
1-2-H1	Red coarse sandstone	596.45	84.40	487.60	148.70	35.10	1.01	11.40	14.40	2.28	15.50	5.60	4.07	2.17	4.09	15.10	0.44
1-13-H4	Red coarse sandstone	620.25	101.00	535.30	166.00	46.70	1.44	9.77	14.30	2.66	18.30	10.20	3.38	2.66	5.77	18.80	0.20

Table 3. Cont.

Sample Number	Lithology	Depth (m)	Rb	Ba	Sr	Zr	Hf	Y	Pb	Sc	V	Cr	Cu	Co	Ni	Zn	Mo
1-20-H6	Red coarse sandstone	624.95	123.00	568.80	176.40	62.60	1.82	11.80	17.70	3.60	25.40	14.10	5.18	3.75	8.60	29.40	0.37
2-U5	Red fine sandstone	329.12	128.00	525.20	148.10	101.00	4.29	12.20	16.80	4.05	286.60	16.50	6.80	3.60	8.10	36.30	0.77
1-H1	Red fine sandstone	552.21	111.00	559.40	159.60	50.60	1.52	11.20	15.00	2.38	74.00	7.05	3.20	2.38	4.60	16.40	1.08
1-9-H3	Red coarse sandstone	615.55	81.30	630.40	167.30	32.40	0.97	8.79	14.20	2.24	12.40	6.30	3.90	1.97	5.55	14.40	0.39
1-11-H2	Red coarse sandstone	639.45	103.00	537.80	149.80	44.80	1.37	11.20	14.90	2.42	17.00	5.70	4.37	2.80	5.24	18.10	0.49
1-12-H2	Red coarse sandstone	635.25	106.00	531.70	128.20	72.60	2.12	17.50	17.50	3.29	19.60	9.90	6.63	3.36	6.41	24.80	0.93
	MEAN		104.67	579.13	161.93	61.98	1.94	12.26	17.12	3.14	53.30	10.94	4.98	4.66	8.27	22.97	0.95
3-1-U1	Yellow coarse sandstone	712.39	120.00	431.90	157.60	86.60	2.76	15.70	18.80	3.80	70.60	10.40	17.20	13.50	10.80	17.20	1.70
3-H2	Yellow coarse sandstone	654.15	111.00	559.40	159.60	50.60	1.52	14.70	15.00	2.38	74.00	7.05	3.20	2.38	4.60	16.40	1.08
4-H3	Yellow coarse sandstone	588.34	0.55	21.60	541.70	30.00	0.90	21.00	3.19	83.90	174.20	8.00	56.00	42.70	7.78	5.64	18.20
1-4-H3	Yellow fine sandstone	609.95	87.00	633.80	151.90	59.60	2.01	13.50	14.60	3.46	88.60	14.20	8.31	4.47	8.60	23.30	1.44
1-4-H6	Yellow coarse sandstone	623.95	86.60	535.60	143.90	51.10	1.45	10.80	14.50	3.11	70.30	11.90	3.90	3.14	5.95	21.50	1.04
1-20-H5	Yellow coarse sandstone	599.15	88.90	598.00	159.00	43.90	1.27	14.00	14.10	2.95	207.00	8.50	6.45	2.66	4.68	23.50	1.41
1-1-U12	Yellow coarse sandstone	617.45	83.90	541.70	174.20	82.30	2.17	12.84	18.20	5.64	56.60	30.00	7.78	17.40	42.70	56.00	0.55

Table 3. Cont.

Sample Number	Lithology	Depth (m)	Rb	Ba	Sr	Zr	Hf	Y	Pb	Sc	V	Cr	Cu	Co	Ni	Zn	Mo
3-2-H8	Yellow coarse sandstone	754.95	87.50	658.00	177.50	50.40	1.46	10.30	16.50	3.39	17.90	24.30	5.25	3.30	9.20	24.90	0.49
1-2-U2	Yellow fine sandstone	606.80	120.00	652.60	184.20	57.10	1.81	7.96	18.60	2.97	577.20	11.30	11.40	5.84	6.11	24.50	0.67
1-9-H4	Yellow coarse sandstone	625.05	91.60	588.30	171.80	42.20	1.09	12.50	14.70	2.55	43.30	8.60	5.63	4.23	6.03	18.40	0.59
	MEAN		87.71	522.09	202.14	55.38	1.64	13.33	14.82	11.42	137.97	13.43	12.51	9.96	10.65	23.13	2.72
1-2-U6	Uranium ore body	609.05	86.20	660.20	187.20	37.10	1.06	8.60	27.90	2.16	23.00	8.80	7.12	6.39	7.30	16.70	3.49
1-2-U11	Uranium ore body	612.95	85.90	348.00	143.60	52.80	1.38	9.68	25.20	3.25	146.20	14.00	6.02	35.80	25.20	37.60	21.20
1-2-U18	Uranium ore body	624.15	129.00	465.00	158.90	201.00	5.46	28.60	54.10	9.47	110.20	36.90	77.80	105.00	91.20	85.00	40.50
1-4-U14	Uranium ore body	633.30	96.40	1960.00	202.40	67.80	2.04	42.60	15.90	4.57	65.00	19.20	12.40	42.60	27.50	106.00	144.00
1-13-U5	Uranium ore body	601.30	78.50	561.70	160.00	40.70	1.14	10.30	17.90	2.74	50.50	10.80	6.07	26.10	16.60	124.00	1.48
1-13-U8	Uranium ore body	603.15	84.80	136.20	151.10	75.80	2.06	11.30	27.10	4.83	41.90	19.20	7.46	21.00	16.60	45.60	9.11
1-13-U15	Uranium ore body	607.50	97.10	511.40	134.60	82.40	2.40	15.60	118.00	4.69	31.70	16.00	9.77	45.20	40.30	36.10	0.75
1-20-U2	Uranium ore body	606.70	83.20	393.00	100.30	54.70	1.80	14.00	14.50	3.26	149.40	12.20	5.48	16.40	11.80	19.20	1.54
1-20-U4	Uranium ore body	607.55	95.90	565.90	143.50	81.80	2.49	14.40	16.30	3.96	43.10	17.50	5.33	6.73	8.80	18.00	16.70
1-20-U6	Uranium ore body	609.05	91.70	657.60	167.60	50.00	1.64	9.62	15.40	2.85	57.90	10.40	4.23	6.66	7.20	23.20	9.80
	MEAN		92.87	625.90	154.92	74.41	2.15	16.47	33.23	4.18	71.89	16.50	14.17	31.19	25.25	51.14	24.86

Table 4. Results of REE analyses of sandstones from the Saihan Formation in the study area.

Sample Number	Lithology	Depth (m)	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
3-1-U3	Gray middle sandstone	713.34	16.63	31.00	3.75	13.83	2.56	0.59	2.13	0.36	1.92	0.43	1.11	0.18	1.17	0.18
3-1-U8	Gray coarse sandstone	714.64	24.90	45.40	5.52	19.80	3.59	0.69	3.05	0.52	2.72	0.59	1.52	0.25	1.62	0.25
3-U11	Gray glutenite	763.47	18.30	36.10	4.55	16.50	3.44	0.73	2.99	0.48	2.47	0.56	1.37	0.24	1.39	0.23
1-4-U1	Gray coarse sandstone	612.80	29.00	56.40	6.69	23.60	4.32	0.76	3.37	0.62	3.51	0.72	1.96	0.32	1.86	0.26
1-4-U3	Gray coarse sandstone	613.40	25.40	48.00	5.64	19.10	3.31	0.64	2.21	0.39	2.07	0.42	1.21	0.22	1.30	0.18
1-4-U7	Gray coarse sandstone	615.05	32.50	58.20	6.68	22.30	3.49	0.55	2.37	0.41	2.13	0.43	1.19	0.22	1.29	0.18
1-4-U13	Gray coarse sandstone	619.03	19.50	38.00	4.59	15.80	2.98	0.56	2.09	0.37	1.86	0.38	1.04	0.18	1.09	0.15
1-20-U10	Gray coarse sandstone	611.30	22.00	40.50	4.81	16.20	2.72	0.55	1.84	0.33	1.79	0.36	1.05	0.19	1.09	0.16
1-15-U2	Gray fine sandstone	651.50	44.20	97.40	9.89	36.00	6.25	0.98	4.60	0.72	3.62	0.69	1.85	0.29	1.80	0.27
1-15-U4	Gray fine sandstone	652.35	59.40	118.00	13.40	47.60	8.18	1.28	5.94	0.94	4.82	0.96	2.66	0.42	2.64	0.40
	MEAN		29.18	56.90	6.55	23.07	4.08	0.73	3.06	0.51	2.69	0.55	1.50	0.25	1.53	0.23
3-1-U10	Red coarse sandstone	715.24	51.00	76.60	9.15	31.10	5.47	0.82	4.10	0.68	3.65	0.74	2.01	0.33	1.97	0.27
3-3-H2	Red coarse sandstone	686.85	13.60	25.80	3.20	11.20	2.05	0.49	1.60	0.28	1.45	0.30	0.81	0.15	0.78	0.11
1-2-H1	Red coarse sandstone	596.45	15.80	28.80	3.58	12.90	2.50	0.57	1.90	0.34	1.93	0.40	1.10	0.20	1.12	0.15
1-13-H4	Red coarse sandstone	620.25	17.50	32.00	3.98	14.10	2.54	0.53	1.78	0.31	1.63	0.34	0.91	0.17	0.95	0.13

Table 4. Cont.

Sample Number	Lithology	Depth (m)	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
1-20-H6	Red coarse sandstone	624.95	21.00	38.90	4.71	16.50	2.89	0.65	2.14	0.37	1.98	0.41	1.12	0.20	1.16	0.16
2-U5	Red fine sandstone	329.12	21.10	39.20	4.54	15.40	2.74	0.56	1.95	0.36	1.93	0.42	1.16	0.21	1.25	0.17
1-H1	Red fine sandstone	552.21	23.00	44.90	5.38	18.80	3.52	0.82	2.78	0.42	1.97	0.44	1.12	0.20	1.16	0.20
1-9-H3	Red coarse sandstone	615.55	16.30	32.50	3.64	13.10	2.37	0.54	1.69	0.29	1.54	0.30	0.84	0.14	0.81	0.12
1-11-H2	Red coarse sandstone	639.45	21.90	43.10	4.91	17.40	3.00	0.57	2.27	0.37	2.01	0.40	1.10	0.18	1.13	0.16
1-12-H2	Red coarse sandstone	635.25	31.10	59.20	6.95	24.60	4.35	0.69	3.17	0.55	2.83	0.58	1.72	0.27	1.76	0.25
	MEAN		23.23	42.10	5.00	17.51	3.14	0.62	2.34	0.40	2.09	0.43	1.19	0.20	1.21	0.17
3-1-U1	Yellow coarse sandstone	712.39	44.20	83.50	9.24	32.50	5.28	0.83	3.50	0.55	2.76	0.54	1.54	0.24	1.56	0.24
3-H2	Yellow coarse sandstone	654.15	23.00	45.60	5.45	18.90	3.71	0.80	2.99	0.46	2.44	0.56	1.50	0.29	1.66	0.28
4-H3	Yellow coarse sandstone	588.34	34.70	63.50	7.39	26.60	4.96	0.91	4.17	0.65	3.60	0.74	2.11	0.37	2.34	0.37
1-4-H3	Yellow fine sandstone	609.95	21.50	42.40	4.90	17.40	3.24	0.59	2.36	0.42	2.30	0.47	1.31	0.23	1.33	0.18
1-4-H6	Yellow coarse sandstone	623.95	17.90	34.20	4.16	14.80	2.63	0.53	1.92	0.35	1.85	0.38	1.09	0.19	1.12	0.16
1-20-H5	Yellow coarse sandstone	599.15	21.40	43.30	5.02	17.90	3.40	0.71	2.72	0.48	2.52	0.50	1.35	0.23	1.29	0.18
1-1-U12	Yellow coarse sandstone	617.45	18.09	35.00	4.27	15.46	2.94	0.66	2.65	0.46	2.45	0.54	1.39	0.24	1.46	0.23

Table 4. Cont.

Sample Number	Lithology	Depth (m)	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
3-2-H8	Yellow coarse sandstone	754.95	18.50	35.60	4.23	14.70	2.67	0.56	1.90	0.33	1.81	0.38	1.04	0.20	1.14	0.17
1-2-U2	Yellow fine sandstone	606.80	21.60	41.80	4.80	16.30	2.68	0.48	1.68	0.28	1.44	0.30	0.82	0.16	0.92	0.13
1-9-H4	Yellow coarse sandstone	625.05	21.80	43.80	5.03	18.00	3.15	0.62	2.36	0.39	2.12	0.43	1.20	0.19	1.24	0.19
	MEAN		24.27	46.87	5.45	19.26	3.47	0.67	2.63	0.44	2.33	0.48	1.33	0.23	1.41	0.21
1-2-U6	Uranium ore body	609.05	19.30	37.40	4.25	14.60	2.59	0.51	1.89	0.31	1.53	0.32	0.85	0.16	0.87	0.12
1-2-U11	Uranium ore body	612.95	14.90	37.30	4.74	16.10	2.46	0.50	1.71	0.28	1.46	0.31	0.85	0.16	0.88	0.12
1-2-U18	Uranium ore body	624.15	43.80	82.20	10.10	35.80	6.40	1.08	4.74	0.86	4.67	0.98	2.78	0.47	2.93	0.42
1-4-U14	Uranium ore body	633.30	19.80	39.30	5.33	21.00	4.74	1.02	4.65	0.88	5.04	1.07	2.86	0.40	2.22	0.32
1-13-U5	Uranium ore body	601.30	10.40	27.00	4.65	18.90	2.44	0.52	1.71	0.31	1.75	0.35	0.98	0.18	1.00	0.13
1-13-U8	Uranium ore body	603.15	24.10	44.60	5.14	17.60	2.98	0.57	2.03	0.37	2.00	0.42	1.23	0.22	1.32	0.19
1-13-U15	Uranium ore body	607.50	23.20	46.20	5.63	19.10	3.45	0.64	2.44	0.49	2.85	0.59	1.64	0.28	1.69	0.23
1-20-U2	Uranium ore body	606.70	24.90	49.60	5.76	19.90	3.64	0.52	2.50	0.44	2.40	0.48	1.35	0.23	1.36	0.18
1-20-U4	Uranium ore body	607.55	33.80	62.50	7.35	25.00	4.43	0.64	2.87	0.49	2.59	0.52	1.46	0.25	1.51	0.21
1-20-U6	Uranium ore body	609.05	24.30	47.00	5.41	19.00	3.22	0.52	2.08	0.34	1.80	0.35	0.97	0.18	1.04	0.14
	MEAN		23.85	47.31	5.84	20.70	3.64	0.65	2.66	0.48	2.61	0.54	1.50	0.25	1.48	0.21

5. Discussion

5.1. Spatial Architecture and Dynamic Evolution of Interlayer Oxidation Zones

5.1.1. Distribution Pattern of Interlayer Oxidation Zone

The red sandstone dominates the stratigraphic framework of the study area, exhibiting the most extensive spatial distribution. Vertically spanning the entire stratigraphic column, its thickness varies considerably across the region, with measurements ranging between approximately 32.58 m and 112.08 m (average thickness: 79.09 m). Planar distribution patterns reveal a distinctive fan-shaped configuration with lobate extensions, characterized by pronounced thickening trends in the northwestern and southeastern sectors and comparatively thinner accumulations within the central zone (Figure 7a,d). In contrast, the yellow sandstone displays the most limited spatial development, forming vertically discontinuous, thin-bedded layers with thicknesses varying from negligible presence (0 m) to a maximum of 11.4 m (average: 3.15 m). Its planar geometry comprises isolated, irregular “island-like” clusters aligned along a prominent southwest–northeast structural trend (Figure 7b,d).

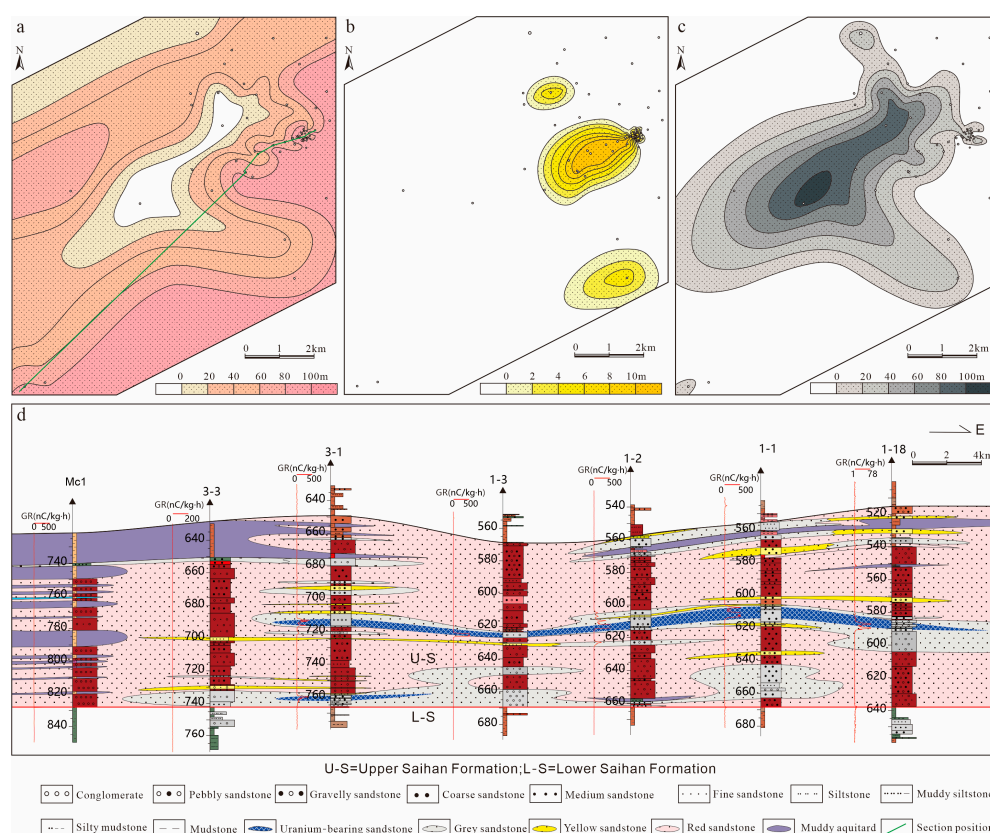


Figure 7. Spatial distribution pattern of the interlayer oxidation zone in the Saihan Formation. (a) Thickness distribution plan of red sandstone; (b) thickness distribution plan of yellow sandstone; (c) thickness distribution plan of gray sandstone; (d) vertical profile of the interlayer oxidation zone in the Saihan Formation.

The gray non-mineralized sandstone exhibits intermediate thickness variations (0–23.79 m; average: 8.87 m), occurring as vertically intercalated lenses within the dominant red sandstone sequence. Its planar distribution mimics a composite fan-shaped morphology oriented southwest–northeast, attaining maximum cumulative thicknesses exceeding 60 m in the central portion of the study area (Figure 7c,d). Uranium ore bodies, with thicknesses ranging from absent (0 m) to 13.8 m (average: 4.34 m), manifest as vertically discontinuous bands exhibiting strong spatial affinity with gray sandstone units within reduction-dominated zones (Figure 7d).

5.1.2. Evolution of Interlayer Oxidation Zones

The dynamic evolution of oxidation zones is governed by the interplay between oxygenated uranium-bearing fluid migration and redox front propagation. During initial fluid infiltration, sandbodies adjacent to primary permeability conduits undergo rapid and extensive oxidative alteration. With progressive fluid advancement and oxygen consumption, oxidation intensity diminishes systematically, creating a hierarchical zonation. Influenced by the heterogeneity of the uranium reservoir, the oxidation intensity forms layered zones in both the plane and vertical directions. Fully oxidized domains represent early-stage fluid pathways where oxygen availability permitted complete mineralogical transformation. Subsequent oxygen depletion results in partial oxidation preservation, while terminal stages of fluid migration preserve pristine gray sandbodies along distal pathways.

A quantitative classification framework for oxidation subzones has been established based on the proportional thickness of oxidized versus total sandbody intervals: (1) strong oxidation zone—complete oxidative alteration (100% oxidation ratio); (2) weak oxidation zone—high-degree oxidation (80%–100% oxidation ratio); (3) transition zone—partial oxidation with redox gradient development (0%–80% oxidation ratio) and (4) reduction zone—unaltered primary lithology (0% oxidation ratio).

A comprehensive analysis of borehole records demonstrates that oxidized sandbodies constitute over 50% of the total stratigraphic thickness across the study area, displaying a progressive northwest-to-southeast decrease in oxidation ratios that inversely correlates with gray sandstone thickness distributions (Figures 7c and 8a). The complete absence of unoxidized gray sandstone sequences underscores the pervasiveness of oxidative processes in the system. Planar mapping delineates extensive strong oxidation domains, narrow weak oxidation corridors, and sinuous oxidation front boundaries with complex geometric irregularities.

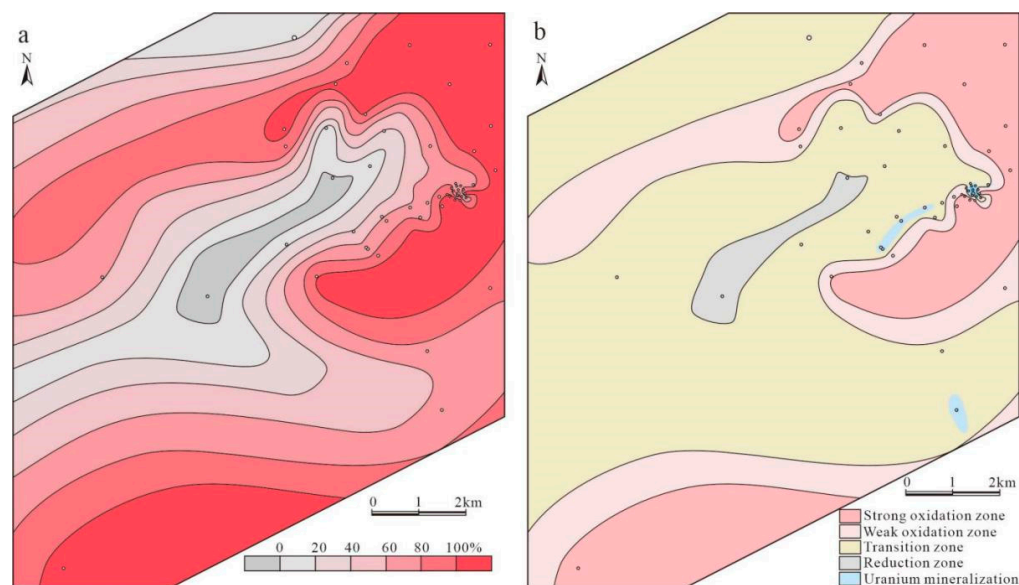


Figure 8. Plane characteristics of interlayer oxidation zone in Saihan Formation. (a) Contour map of oxidized sand body ratio; (b) plane zoning of interlayer oxidation zones and spatial configuration relationship of uranium mineralization bodies.

Critical metallogenic relationships emerge in the transition zones, where uranium mineralization demonstrates strict spatial confinement to redox interface proximal environments adjacent to oxidation fronts (Figure 8a). These transitional domains represent optimal geochemical traps, where fluctuating redox conditions facilitate uranium precipitation and concentration. The spatial configuration and intensity of oxidation processes

are fundamentally controlled by hydrodynamic parameters governing fluid flux rates, oxygen replenishment dynamics, and permeability architecture. The established quantitative zonation criteria provide a robust predictive framework for identifying and prioritizing exploration targets within these uranium-enriched transitional environments.

5.2. Controlling Factors of Interlayer Oxidation

This study reveals that the development of interlayer oxidation zones is directly governed by the sandbody thickness, sand-to-mud ratio, and thickness/number of mudstone interlayers, while sedimentary environment serves as the primary innate factor controlling reservoir heterogeneity within the same stratigraphic unit under consistent tectonic settings [1,23,57,58].

5.2.1. Influence of Reservoir Architecture and Geometry

Reservoir heterogeneity impacts oxidation zone development through sandbody scale, barrier layer thickness, and dark mudstone distribution. Oxidation subzones predominantly occur in sandbodies with moderate thickness (40–80 m; Figure 9a) and sand-to-mud ratios of 40%–80% (Figure 9b), accompanied by 2–10 mudstone barriers (avg. 20 m thick). In contrast, reduction zones develop in thicker sandbodies (~100 m) with higher sand-to-mud ratios (~80%) and fewer mudstone barriers (2–8 layers, 40–80 m thick). Large-scale, well-connected sandbodies in the study area enhance oxidant fluid penetration, whereas excessive barrier layers impede fluid migration and oxidation capacity.

5.2.2. Sedimentary Facies Control

Sedimentary facies mapping of the upper Saihan Formation (Figure 10) demonstrates the following: Oxidation zones cluster in braided channels and channel margins. Transition zones dominate braided distributary channels and floodplain deposits. Reduction zones occur primarily in channel margins. Braided and distributary channels host thick, coarse-grained, well-connected sandbodies (pebbly/coarse-medium sandstone), serving as major pathways for oxygenated uranium-bearing fluids. Floodplains and channel margins, characterized by heterogeneous sandbodies and prolonged water retention, slow fluid migration and reduce oxidation capacity, promoting uranium precipitation at the oxidation fronts. Transitional areas between braided channels and channel margins are optimal for uranium enrichment.

5.3. Relationship Between Interlayer Oxidation and Uranium Mineralization

Interlayer oxidation reflects water–rock interactions [7,27,59–63]. Key geochemical correlations include the following: positive total sulfur vs. S^{2-} in mineralized sandstone (Figure 11a), indicating sulfur enrichment linked to sulfide formation; positive organic carbon vs. Fe^{2+}/S^{2-} (Figure 11b,c), highlighting redox coupling; and positive Fe^{2+} vs. S^{2-} (Figure 11d), reflecting synchronous enrichment during mineralization.

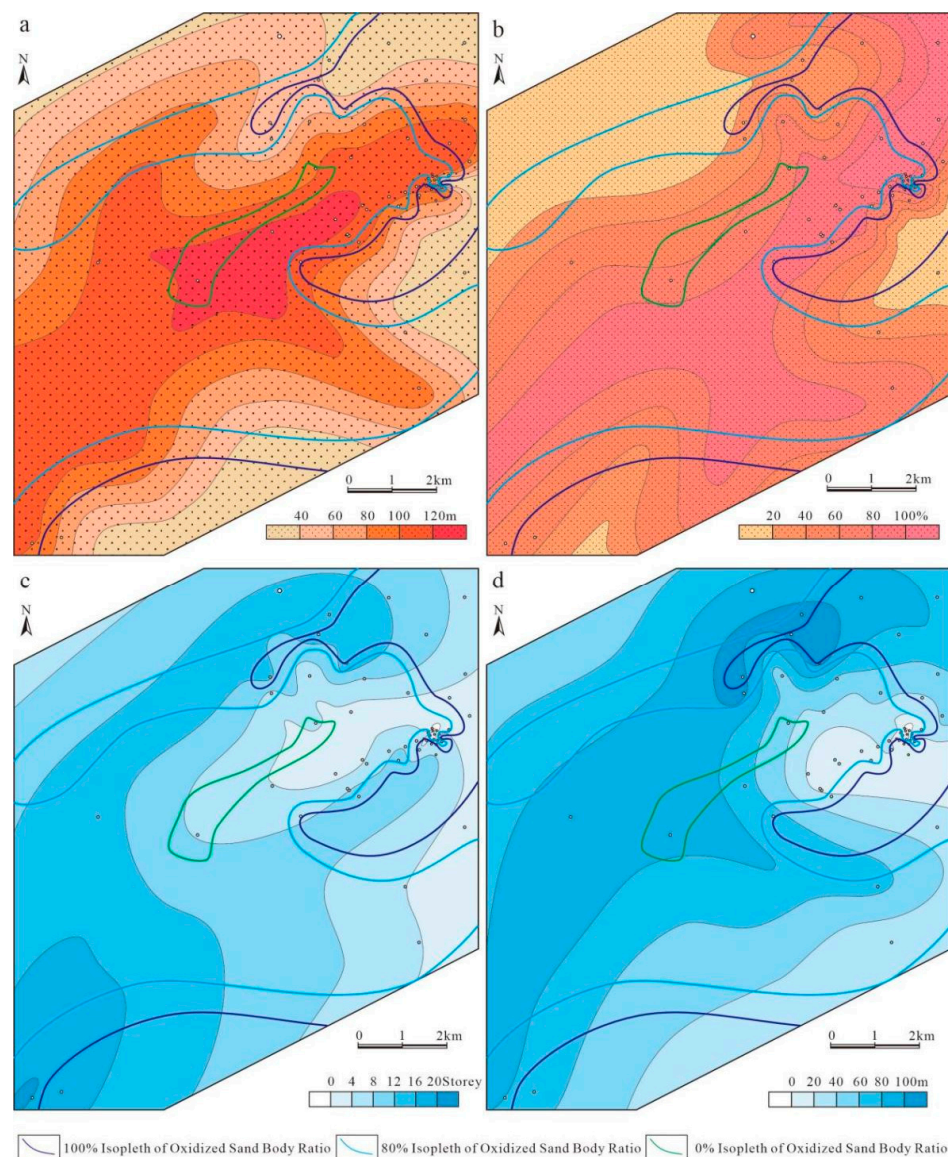


Figure 9. Relationship between geometric shape of uranium reservoirs and interlayer oxidation zone in uranium deposit; (a) relationship diagram between sand body thickness and interlayer oxidation zone; (b) relationship between sand content and interlayer oxidation zone in sand body; (c) relationship diagram between the number of barrier layers and interlayer oxidation zones; (d) relationship between barrier layer thickness and the interlayer oxidation zone.

Uranium from weathered granitic sources enters groundwater as U^{6+} (uranyl complexes). Oxygenated fluids oxidize organic matter, $Fe^{2+} \rightarrow Fe^{3+}$ (limonite/hematite formation), and $U^{4+} \rightarrow U^{6+}$, mobilizing uranium. Oxygen depletion triggers the reduction process as follows: $Fe^{3+} \rightarrow Fe^{2+}$ combines with S^{2-} to form pyrite, while uranyl complexes reduce to pitchblende (UO_2). Residual U^{4+} reacts with SiO_4^{4-} to form coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$), occurring as colloids around quartz or pyrite (Figure 3). This process drives decreasing Th/U ratios from strong oxidation $\rightarrow$ weak oxidation $\rightarrow$ reduction $\rightarrow$ mineralized transition zones (Figures 6 and 12). Concurrently, transition metals (Co, Ni, Zn, and Mo) co-enrich with uranium in transitional zones due to differential ligand complexation (Figures 6 and 12).

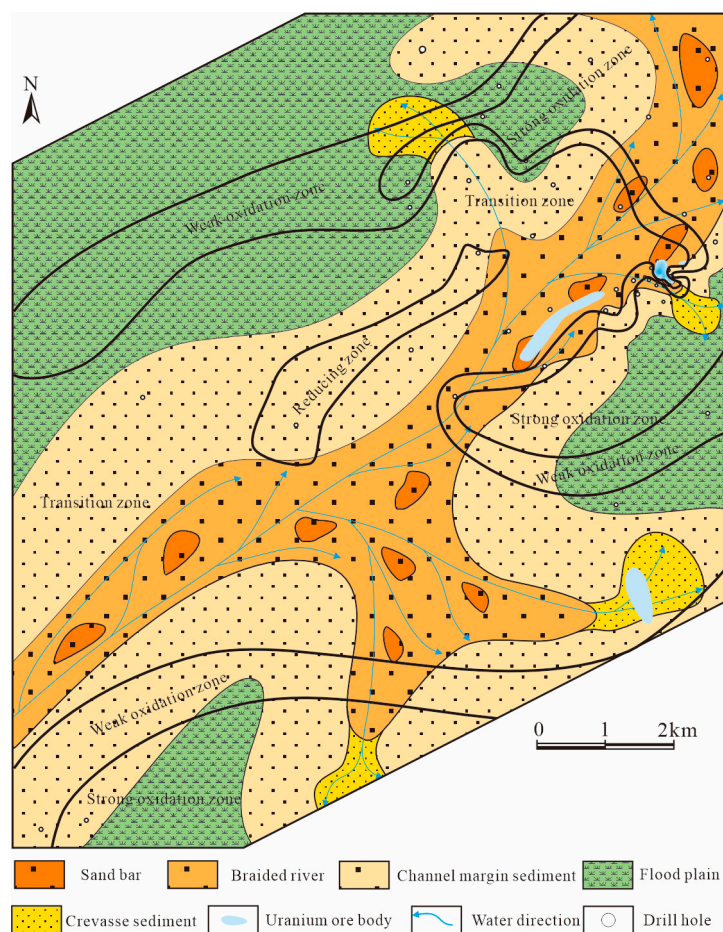


Figure 10. Spatial relationship between the sedimentary system, interlayer oxidation zone, and uranium mineralization in the upper part of the Saihan Formation.

During the Paleogene period, tectonic inversion occurred in the Erlian Basin. This led to the uplift area in the southern part of the Naomugen Depression, causing the Saihan Formation uranium reservoir to be exposed to the surface and subjected to erosion. This exposure allowed surface fluids to flow directly into the uranium reservoir. In the Sonid Uplift area, located in the southern Naomugen Depression of the Erlian Basin, uranium-enriched intermediate-acidic granitic plutons underwent weathering. Uranium within these plutons was released and subsequently carried by oxygenated fluids that infiltrated the Saihan Formation uranium reservoir [64–67].

When the oxygenated, uranium-bearing fluids entered the uranium reservoir, oxygen within the fluids reacted with reductants, such as organic matter, present in the gray sandbodies. This reaction reduced the reducing capacity and increased the oxidizing capacity of the sandbodies. Plant debris and other organic matter within the sandstones decomposed under the oxidizing conditions, causing the environment-sensitive parameters of the sandstone to progressively change from a reduced zone, through a transitional zone and a weakly oxidized zone, to a strongly oxidized zone (Figure 12). Concurrently, U(IV) within the gray sandbodies was oxidized to U(VI), forming uranyl complex ions that migrated with the flowing fluids. As the oxygen in the fluids became gradually depleted, the reducing capacity of the sandbodies increased while their oxidizing capacity diminished, forming an interlayer oxidation front. Near this interlayer oxidation front, the uranyl complex ions, now lacking oxygen, were reduced and precipitated as pitchblende (uraninite). Some U(IV) reacted with SiO_4^{4-} to form coffinite, which occurs in colloidal form around quartz clasts or pyrite grains (Figure 3). Consequently, sandstone-hosted

uranium mineralization primarily developed within the transitional zone, proximal to the interlayer oxidation front.

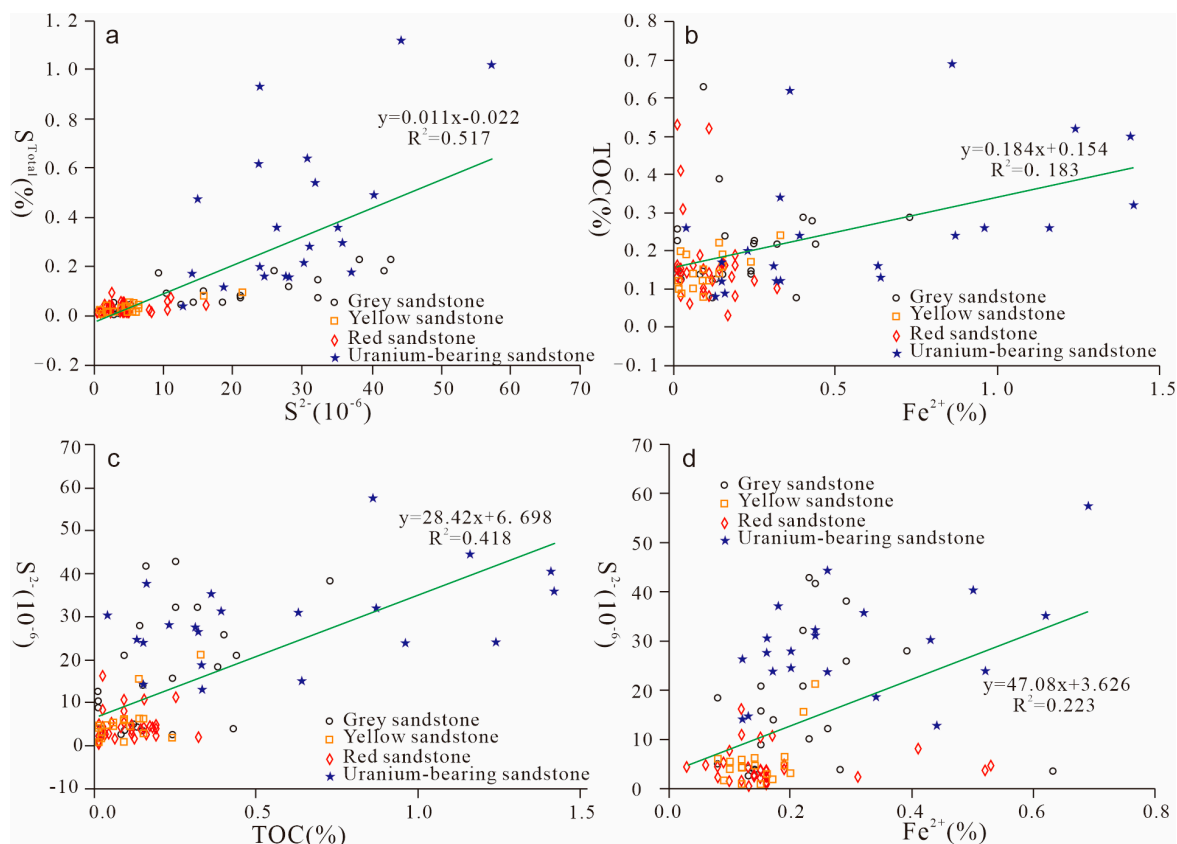
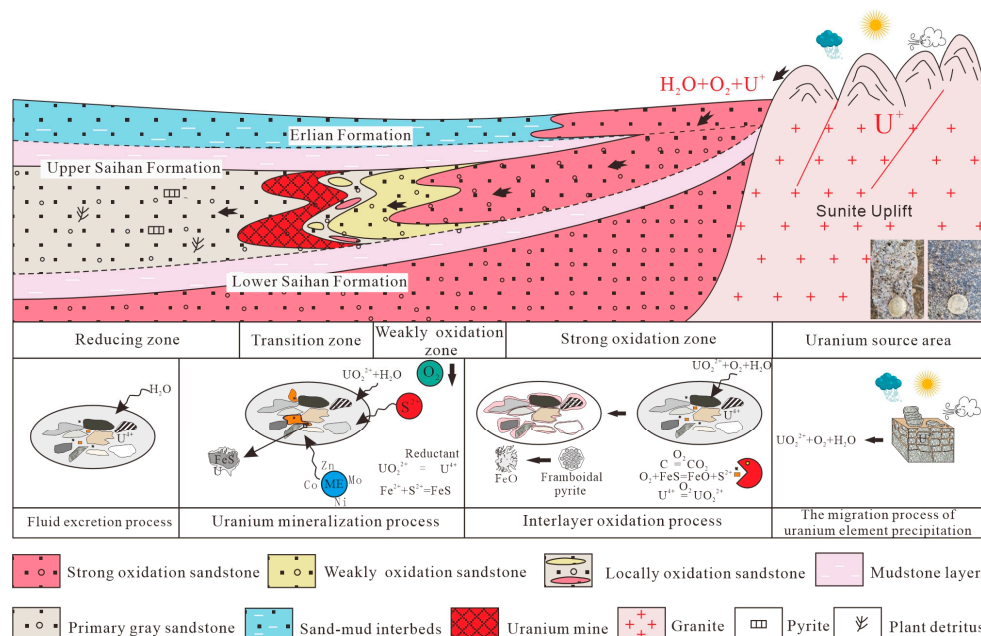


Figure 11. Relationship diagram of environmental sensitive parameters of Saihan Formation sandstone. (a) Relationship diagram of total sulfur and divalent sulfur; (b) relationship diagram of organic carbon and ferrous iron; (c) relationship diagram of divalent sulfur and organic carbon; (d) relationship diagram of divalent sulfur and ferrous iron.



6. Conclusions

Through the integrated analysis of interlayer oxidation zones in the Saihan Formation of the Wulanchabu Depression, Erlian Basin, the following conclusions are drawn:

- (1) The sandbodies comprise red sandstone (strong oxidation), yellow sandstone (weak oxidation), gray mineralized sandstone (transition zone), and primary gray sandstone (reduction zone). While clastic mineral content shows minimal variation across zones, feldspar dissolution is prevalent in oxidized regions. Environmentally sensitive parameters increase progressively from strong oxidation to transition zones, with Co, Ni, Zn, and Mo enrichment in mineralized areas.
- (2) Interlayer oxidation development is controlled by reservoir heterogeneity and sedimentary environments. Oxidation subzones occur in sandbodies with moderate thickness (40–80 m), sand-to-mud ratios (40%–80%), and 2–10 mudstone barriers (~20 m thick), predominantly in braided channels and channel margins. Reduction zones form in thicker sandbodies (~100 m) with higher sand contents (~80%) and fewer barriers (2–8 layers, 40–80 m thick), mainly in channel margins. Transition zones dominate braided distributary channels and floodplains.
- (3) Uranium mineralization involves redox-driven fluid–rock interactions: Oxygenated fluids oxidize $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$, $\text{S}^{2-} \rightarrow \text{SO}_4^{2-}$, and $\text{U(IV)} \rightarrow \text{U(VI)}$ (uranyl migration). Oxygen depletion triggers $\text{Fe}^{3+} \rightarrow \text{Fe}^{2+}$ reduction, forming pyrite with S^{2-} , while uranyl complexes reduce to pitchblende. Partial U^{4+} reacts with SiO_4^{4-} to form coffinite, accompanied by transition metal enrichment.

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Conflicts of Interest: Author Yang Liu was employed by the company China Shaanxi Nuclear Industry Group Geological Survey Institute Co., Ltd. Authors Ning Luo and Xiaolin Yu were employed by the company PetroChina Huabei Oilfield Company. Author Ming Li was employed by the company PetroChina Jilin Oilfield Company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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