Development characteristics of interlayer oxidation zone type of sandstone uranium deposits in the southwestern Turfan-Hami basin

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Abstract The Turfan-Hami basin is the key area for the exploration of sandstone uranium deposits of the leachable interlayered oxidation zone type. The aim of this study is to shed light on the development characteristics of this type of uranium deposits and provide new clues to further exploration. Detailed study led to the following conclusions: (1) uranium orebodies are hosted mainly in the lower Middle Jurassic Xishanyao Formation and the lower Lower Jurassic Badaowan Formation; (2) the formation of uranium orebodies is closely related to organic matter; (3) the front of the interlayered oxidation zone is snake-shaped in plane and imbricated in the section; the more the interlayered oxidation zone and zonation are developed, the better the uranium mineralization will be; according to lithological and geochemical characteristics, the oxidation zone, the oxidation-reduction transitional zone and the reduction zone can be distinguished; (4) the development of interlayered oxidation zone is controlled by geological structure, underground water, sandstone permeability and other factors; (5) sandstone uranium orebodies hosted in the interlayered oxidation zone are very complicated in spatial distribution, of which some are rolled and plated in shape and some are highly variable in shape.

Keywords: Turfan-Hami basin, interlayered oxidation zone, sandstone uranium deposit, development characteristics.

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The known uranium ore and anomaly occurrences are distributed mainly in the southwestern part of the Turfan-Hami basin. The focus of current exploration is placed on the leachable interlayered oxidation zone type of sandstone uranium deposits.

Uranium deposits in the sedimentary basin can be classified into three types in accordance with their host rock types, i.e. the sandstone-type uranium deposits, the coal rock-type uranium deposits and the mudstone-type uranium deposits. The sandstone-type uranium deposits refer to those uranium deposits occurring in perfectly permeable sandstones, conglomerate-bearing sandstones or conglomerate rocks, overlying and underlying which are developed mudstones and silty rocks as the water-resisting layers. The coal rock-type uranium deposits refer to uranium mineralization in coal measures or coal seems. The mudstone-type uranium deposits refer to those occurring in poorly permeable mudstones, silty mudstones and silty rocks[1]. The sandstone-type uranium deposits are usually large in reserve and suitable for leachable exploration. This type of uranium deposits is the main target exploration type in China at present time. The coal rock-type uranium deposits are considerable in reserve and they are mined as by-products in coal exploitation. The mudstone-type uranium deposits are generally large in metallogenic scale, but uranium orebodies are of dispersed occurrence and are hard to access. So this type of uranium deposits is almost of no economic interest.

According to the theory of uranium metallogenesis, the above three types of uranium deposits are of deuterogenic origin, i.e. these uranium deposits were formed by reworking metallogenesis under the involvement of surface water and underground water. These uranium deposits can also be divided into two subtypes: the phreatic oxidation zone-subtype and the interlayered oxidation zone-subtype. These two subtypes of uranium deposits are different with respect to their hydrodynamic systems. The phreatic oxidation zone-type uranium deposits were formed under the action of gas-charged water and phreatic water while the interlayered oxidation zone-type uranium deposits were formed under the action of interlayered pressure-loaded water.

The interlayered oxidation zone-type sandstone uranium deposits, due to their large-scale mineralization and accessibility for exploration, have attracted great attention of geologists of ore deposits both at home and abroad. Research on the interlayered oxidation zone-type sandstone uranium deposits started earlier abroad, especially in America and the former Soviet Union. Some large-sized interlayered oxidation zone-type sandstone uranium deposits have been found on the Colorado Plateau, in the Wyoming Basin and the coastal plains of Texas of the United States, in the Chu-Salassov Basin and Sirdary Basin of Middle Asia and the Kezelkum Basin. Some common regularities have been established concerning the prognosis of the interlayered oxidation zone-type sandstone uranium deposits and their metallogenic theories, though different types of uranium deposits have different metallogenic rules of their own.

Uranium deposits on the Colorado Plateau are located on the relatively tectonically stable platform margins. The organic matter-rich Jurassic continental-facies sediments constitute the major ore-host strata; the interlayered oxidation zone-type uranium deposits are distributed largely on the margins of various depressions; the orebodies are controlled by the sedimentary system and its spatial development; and post-ore reworking processes are noticeable in response to the Neotectonic movement[2].

Having influenced by the Cenozoic fold tectonic movement, the pre-Cenozoic strata in the Wyoming Basin were folded and domed, accompanied with intensive volcanic eruption. So, there was a deposited suite of volcanic tuff-rich clastic rocks in the region of the Cenozoic intermountain basin developed on the Cenozoic folded basement, which constitute the main ore-host strata in this region. Orebodies are usually distributed on the margins of the basin adjacent to the uranium provenance. The uranium source has played an important role in uranium mineralization. The spatial development of orebodies is controlled by the sedimentary facies of ore-host layers. The orebodies are rolled in shape and show obvious signs of multi-phase migration and enrichment of uranium.

The basement of the uranium mining districts in the Chu-Salassov Basin and Sirdary Basin is tectonically stable. Sedimentary terrains are of wide development in space. The attitudes of rock layers are gentle and underground waters can flow over long distance along the layers to form large-scale interlayered oxidation zones. The mineralization domain is located within the basin depression, large in scale with no sign of remarkable subsequent reworking. The uranium field in the Kezelkum Basin has been affected by the Tianshan folded zone, where tectonic movement was relatively intensive, so the development of interlayered oxidation zone is limited in space[1)].

The Turfan-Hami basin is situated on the Kazakstan plate at the juncture of the three ancient plates ——the Kazakstan plate, the Siberian plate and the

1) Beijing Research Institute of Uranium Geology, The uranium deposits geology in Russia and Mongolia (in Chinese), 1998, 17—29.

Tarim plate. Its regional geotectonic setting is located between the North Tianshan suture zone and the Kelamali suture zone, with a double basement. And the upper basement is different between the south and the north, which is the principal feature of the basement of the Turfan-Hami basin. The Qoltag and Mt. Bogda tectonic zones are the major two tectonic zones which created favorable conditions for the formation of the Turfan-Hami basin. The two tectonic zones played a very important role in controlling the sedimentary framework of the Turfan-Hami basin and the material source. Uranium metallogenesis is a long-term process and uranium enrichment is a sustained process. The uranium source regions are predominated by orogenic fold zones, where uranium resources are abundant and the metallogenic conditions are perfect. The major ore field is located on the southern margin of the basin, where Neotectonic movement was relatively weak and hence the deuterogenic reworking of orebodies is not conspicuous.

Not only the sandstone-type uranium deposits, but also the coal rock- and the mudstone-type uranium deposits have been recognized in the southwestern part of the Turfan-Hami basin. The sandstone-type uranium deposits are distributed largely in the areas of Shihongtan, Baishitan, etc. The phreatic oxidation zone- type and interlayered oxidation zone-type uranium mineralizations are of extensive development in the southwestern part of the basin, but the former type is of no economic value. The interlayered oxidation zone-type uranium mineralization is well developed in the southwestern part of the Turfan-Hami basin, and the orebodies are large in size, hence favoring leachable exploitation. This type of ores is of great commercial importance. So, in the southwestern part of the Turfan-Hami basin the uranium exploration should be focused on the interlayered oxidation zone-type sandstone uranium deposits. The development and geochemical characteristics of oxidation zones for this type of uranium mineralization are the key objects of study.

This work has been accomplished on the basis of almost two years of field investigation, a number of experiments and much laboratory organization work, in conjunction with the drill core data provided by the Northwest 203 Institute under the Ministry of Nuclear Industry of China.

1 The occurring horizons of the interlayered oxidation zone type of uranium deposits

The uranium-occurring horizons in the southwestern part of the Turfan-Hami basin belong to the lower Lower Jurassic Badaowan Formation, the upper Lower Jurassic Sangonghe Formation and the lower Middle Jurassic Xishanyao Formation.

According to the latest drill core data, uranium orebodies are hosted mainly in the Xishanyao and Badaowan formations, of which the Xishanyao Formation uranium orebodies are most perfectly developed. The uranium mineralization zones developed in drill cores such as zk63-12, zk63-14, zk47-5 and zk55-5 are hosted in the Xishanyao Formation, with zk47-5 as a typical uranium mineralization zone. Uranium ore is seen at the depth of 262.5 m in this drill core, with the grade up to 0.3415%. Also in the same horizon, uranium mineralization in the drill core zk55-5 has a grade of 0.2451%. The ore-host rocks are grey-greyish green medium coarse-grained sandstones and conglomerate-bearing coarse sandstones, with the orebodies being 8.5 m in thickness. The obvious discriminative marker of orebodies is their location in between coal seams M_3 and M_4 (fig. 1(a)). The two coal seams are very thick. Coal seam M_3 is 1.2—9 m thick, while coal seam M_4 is of multi-stratification, with a total thickness of 2.1—17 m. The two coal seams are stably developed and characterized by abundant plant fossils, high differentiation of species and extensive occurrence of plant detritus and plant fossils. Fossil layers such as "*Equisetites*", "*Cladophlebis*" and "*Phoenicopsis*" fossil layers have been distinctively identified in the drill cores[1)].

1) Yang Dianzhong, Stratigraphic division of the Jurassic in the southwestern part of the Turfan-Hami basin and uranium organic geochemistry (in Chinese) (Dissertation), Beijing Institute of Geology, Ministry of Nuclear Industry, 2002, 53—61.

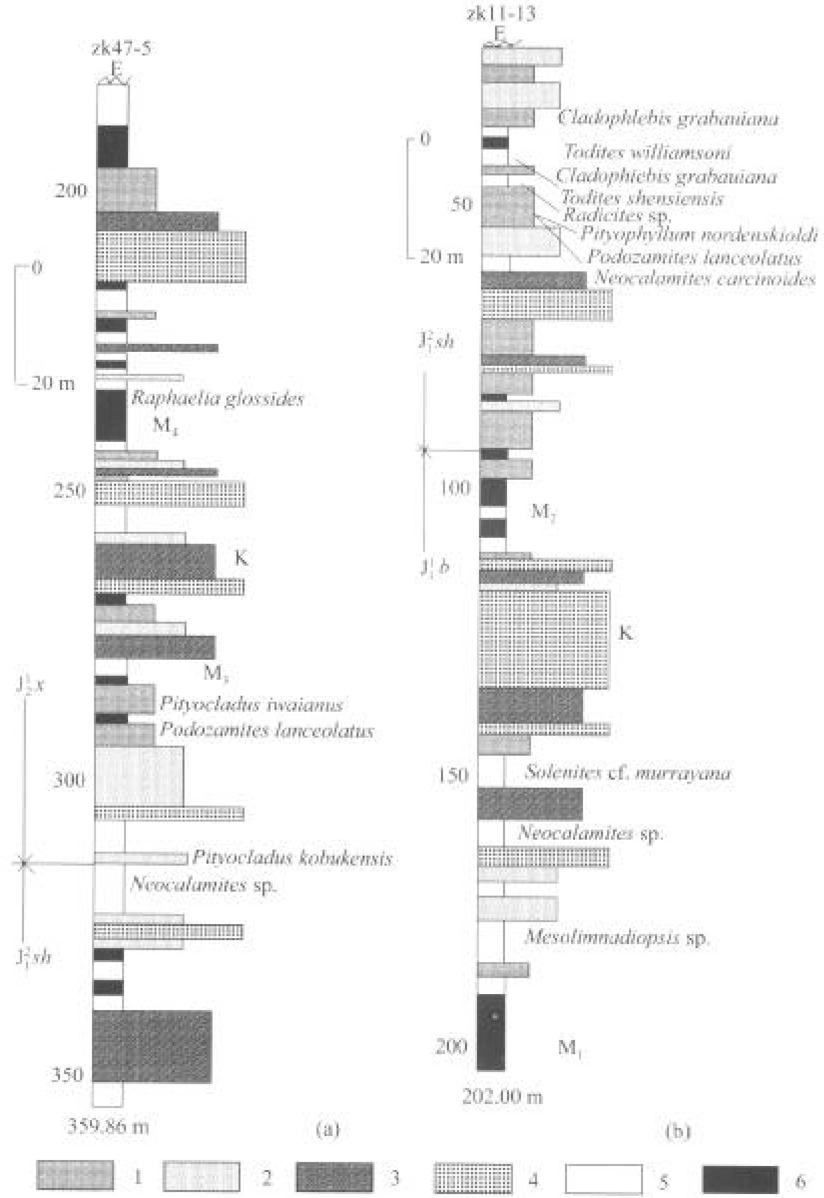


Fig. 1. Histograms of uranium orebodies occurring in the Xishanyao Formation (a) and in the Badaowan Formation (b). 1, Siltstone; 2, fine sandstone; 3, coarse sandstone; 4, conglomerate rock; 5, mudstone; 6, coal seam. E, Eocene brick red sandy conglomerate rock; M_1, coal seam; J_1b, Badaowan Formation; J_1sh, Sangonghe Formation; J_2x, Xishanyao Formation; K, uranium ore horizon.

Another uranium-bearing sandstone massif occurs in between coal seams M_1 and M_2 of the Badaowan Formation, as is recognized in the drill cores zk27-1, zk23-4 and zk11-13. The ore-bearing sandstone massif revealed in the drill core zk11-13 is 18.2 m thick, and lithologically composed of grayish-white conglomerate-bearing coarse sandstone and conglomerate rock (fig. 1(b)). As compared with the former segment, this ore-bearing horizon is less abundant in plant fossils, though it still contains relatively abundant plant detritus and fossils. A lot of plant detritus is present as inclusions or thin “coal measures” distributed irregularly in the sandstone massif.

It is not an accident phenomenon that these horizons contain so abundant plant organic components and the uranium mineralization there is so well developed. The formation of uranium orebodies is closely related to the extremely abundant plant organic components in the metallogenic environment[2−6].

2 Development characteristics of the interlayered oxidation zone

2.1 Spatial development of the interlayered oxidation zone

The front line of the interlayered oxidation zone in the southwestern part of the Turfan-Hami Basin is snake-shaped in plane and embricated in the section. No. 63 exploration line (table 1) and No. 1 exploration line have basically revealed the development characteristics of the interlayered oxidation zone in the southwestern part of the Turfan-Hami Basin. The development of the interlayered oxidation zone is controlled by geological structure, underground water, sandstone permeability and other factors.

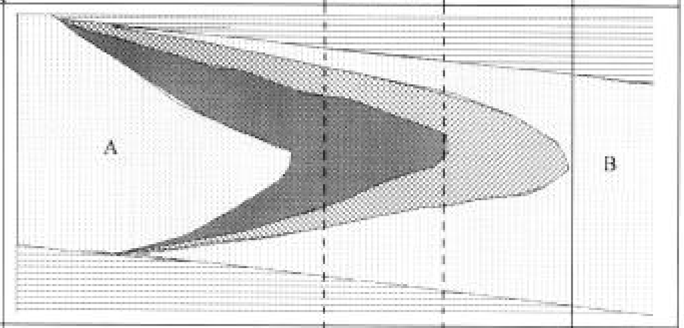
2.2 Zonation of the interlayered oxidation zone

Strong evidence for the zonation of interlayered oxidation zone has been developed from the sandstone-type uranium deposits both at home and abroad[7]. In the southwestern part of the Turfan-Hami Basin is well developed an interlayered oxidation zone. According to its lithological and geochemical characteristics, the interlayered oxidation zone can be divided into the oxidation zone (subdivided into the strong oxidation zone and the weak oxidation zone), the oxidation-reduction transitional zone and the reduction zone. The general feature is that the more obvious the zonation, the better the uranium mineralization will be. The oxidation zone under the control of No. 63 exploration line (in the northern part) is shown in fig. 2. As can be seen from the figure, the interlayered oxidation zone is of distinct zonation and each of the subzones shows unique geochemical characteristics of its own. From the oxidation zone through the oxidation-reduction transitional zone to the reduction zone, the rocks change in color from yellowish-brown, light yellow to grey and greyish-green. At the same time, the content of uranium tends to increase and then decrease. The contents of organic matter and humus also show a tendency of increasing and then decreasing. The content of FeO tends to increase progressively whereas the content of Fe_2O_3 tends to decrease steadily, or even approaching to zero. The contents of S and CaO tend to increase synchronously with those of U.

(i) The oxidation zone. (1) The strong oxidation zone. The rocks were strongly oxidized to become brownish-yellow or purple in color. In the exposure of southwestern Turfan-Hami basin one can find abnormally abundant limonite nodules, in which deuterogenic minerals are well developed, with smectite being dominant. Plant organic matter in the rocks has been

Table 1 Characteristics of the interlayered oxidized zone at No. 63 exploration line (in the southern part)

Drill core No.	Ore appearing position	Apparent thickness/m	Grade (%)	U content/kg・m^{-2}
Zk63-1	87.95—102.05	14.1	0.00173	0.511
	148.95—166.95	18.0	0.00151	0.570
Zk63-2	174.35—184.65	10.30	0.00532	1.151
	212.95—225.3	12.1	0.00175	0.445
Zk63-3	69.95—81.04	11.1	0.00216	0.504
	131.1—141.1	10.0	0.0027	0.573
	217.95—224.5	6.1	0.00221	0.283
Zk63- 4	66.45—79.85	13.4	0.00257	0.72386
	110.15—150.25	40.1	0.00531	4.476
	129.85—137.45	7.6	0.01067	1.7029
Zk63- 6	178.75—190.03	11.28	0.00199	0.477
	222.80—235.27	12.47	0.00356	0.942
	227.35—232.91	4.66	0.00601	0.593
	311.31—317.85	3.36	0.00165	0.118



Characteristics \ Zonation	Oxidation zone: strong oxidation zone	Oxidation zone: weak oxidation zone	Redox zone	Reduction zone
Color	purple yellowish-brown	yellow, light yellow	grey, grayish white	grey, grayish green
U (%)	0.0001	0.0003	0.010	0.0010
FeO/Fe_2O_3	0.57		2.68	4.15
S (%)	3.70	3.88	22.49	4.55
CaO(%)	0.48	0.33	2.47	0.49
C^{org} (%)	0.07	0.08	14.21	0.97
Humus content (%)	2.73	2.94	9.32	4.13
Th (%)	0.0012	0.0009	0.0005	0.0011

Fig. 2. Zonation of the interlayered oxidation zone at No. 63 exploration line in the Turfan-Hami basin. 1, The weak oxidation zone; 2, mudstone; 3, uranium orebody. A, Oxidized sandstone; B, not oxidized sandstone.

oxidized or decomposed almost completely, though plant fossils can still be seen in some horizons. The strong oxidation zone, as compared with the other zones, U content, as well as FeO, S and organic carbon is low, against a high content of Fe_2O_3. (2) The weak oxidation zone. The rocks were oxidized relatively weakly, generally purple or light yellow in color. Organic matter in the oxidized rocks has been almost completely oxidized and decomposed, though some residues are still retained. Pyrite pseudomorphous textures can be observed[8]. In this zone uranium mineralization is rather developed, and in some loci where the oxidation zone is well developed, the rocks contain uranium ores that reach the industrial grade.

(ii) The oxidation-reduction transitional zone. This zone is also referred to as the uranium ore zone, where the rocks are grey, grayish-green and dark grey in color. This zone is the U precipitation-enrichment zone, characterized by abundant organic matter and abnormally high organic carbon and humus, the coexistence of pyrite and limonite, and a high content of pyrite and diversity in pyrite form. The contents of S and CaO in this zone are high relative to the other two zones. That is because part of uranium was transported in the form of uranyl carbonic complexs $(UO_2(CO_3)_3)^{4-}$. In the oxidation-reduction transitional zone, the change of geochemical condition (the decrease of pH value) led to the destruction of uranyl carbonic complexes and the precipitation of uranium as ore. Meanwhile, calcite and dolomite were leached out. Moreover, abundant organic matter present in the oxidation-reduction transitional zone is an important factor leading to the reduction and precipitation of pyrite, and then the pyrite metasomatically reduced U^{+6}, resulting in the coexistence of uranium and pyrite. Clay minerals are predominated by kaolinite. The oxidation-reduction transitional zone under the control of No. 63 exploration line is up to 150—200 m in width.

(iii) The reduction zone. The rocks are grey, grayish-white in color; their uranium contents are obviously lower than those in the oxidation-reduction transitional zone. Limonite has disappeared, the contents of organic carbon and humus tend to decrease, but still higher than those of the oxidation zone.

2.3 Factors affecting the development of the interlayered oxidation zone

As a matter of fact, the formation of interlayered oxidation zone in the geological environment involves very complicated processes. There are many factors that can affect the development of the interlayered oxidation zone, such as climate, topography, geological structure, wall rock property, underground water dynamic condition, sandstone massif permeability, etc[8]. Studies show that the development of interlayered oxidation zones in the Turfan-Hami basin would be affected by the following factors:

(i) Climate. It is known that the characteristics of living organisms can most directly reflect those of the climate. In different climate zones on earth are present different living organisms (including plants and animals). Analysis of the fossil data demonstrates that the development of animal and plant communities started in the Early Jurassic Badaowan Stage, with *Neocalamites*, *Equiselites* and *Czekanaoskia* being dominant, reflecting the then paleoclimate was a warm-moist, seasonally changeable climate. This kind of climate had lasted till the early Middle Jurassic Period. At that time, plant communities were developed and hence a period of prosperity. The uranium ore-hosted strata in the southwestern part of the Turfan-Hami basin were formed just during the early Early Jurassic to the early Middle Jurassic. Abundant plant organic matter contained in the strata created favorable conditions for the formation of uranium ore deposits in the interlayered oxidation zone. Starting from late Middle Jurassic, the climate in the Turfan-Hami basin began becoming hot and dry. In this period, this suite of strata had been denudated and oxidized, thus creating favorable conditions for the development of the interlayered oxidation zone. Geological field observations in the Turfan-Hami basin disclosed that there have been interlayered oxidation zones found either in the exposures or in the drill cores. Although the rocks have been oxidized and become purple or yellowish-brown in color, signs of plants having been oxidized can still be distinguished. This suggests that oxidation took place following the post-diagenesis.

(ii) Topography. The composite topographical features such as medium-to-low mountain ranges, hills and slope-depressions in the southern part of the Turfan-Hami basin are favorable to the formation of interlayered oxidation zone. The U-bearing strata of the Shuixigou Group are mostly distributed in the hilly areas, but there developed highly permeable Neocene and Quaternary conglomerates overlying the lowland areas. Meteoric and ground waters can permeate the conglomerate layers and flow downwards via the permeable sandy conglomerate rocks, thus creating favorable conditions for the formation of interlayered oxidation zones.

(iii) Characteristics of sandstone massif. A sandstone massif is well developed in the Jurassic Shuixigou Group strata in the southwestern part of the Turfan-Hami basin, which is characterized by enormous layers and great thickness of a single layer. Feldspar silicarenite is the dominant lithological type, cemented by argillaceous material. The rock is lose in texture, perfect in permeability and abundant in plant organic matter. In addition, ground water is well developed there[9]. Recent drilling data revealed that the sandstone massif has a total of 8 to 20 layers, with a single layer generally measuring 10—30 m in thickness. The hanging wall of the sandstone massif is generally composed of impermeable mudstone and siltstone layers. Sandstone massives of this kind are favorable to the development of interlayered oxidation zones.

(iv) The development of ground water. The Qoltag Mountain area in the southern part of the Turfan-Hami basin is the ground water-supplying area for ore-bearing strata. Ground water flows mainly from south to north, leading to the development of interlayered oxidation zones on the southern margins. The regional discharge source of ground water is the Aiding Lake and the ground water supply-discharge run-off area is the favorable locus where the sandstone-type uranium mineralization occurs in the interlayered oxidation zone.

3 Development of uranium orebodies and mineralization characteristics

Sandstone uranium orebodies of the interlayered oxidation zone type in the southwestern part of the Turfan-Hami basin are very complicated with respect to their spatial development. Some are rolled or plated in shape and some are highly variable in form. Under the control of the No. 47 exploration line, the sandstone uranium orebodies are generally rolled in shape, with the grade reaching 0.3415%. The rolled ores are 150—180 m in width, with an average width of 42 m.

The uranium orebodies under the control of the No. 63 exploration line also are generally rolled in shape (fig. 3). The ore-host rock is grayish-green con-

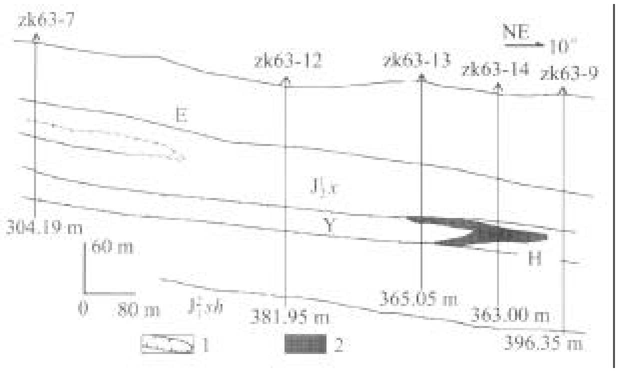


Fig. 3. Development characteristics of uranium orebodies under the control of No. 63 exploration line. 1, Interlayered oxidation zone; 2, uranium deposits (redox zone). Y, Oxidation zone; H, reduction zone; E, Tertiry.

glomerate-bearing coarse sandstone. The upper limb of the orebody under the control of the drill core zk63-13 has a grade of 0.013%, with the uranium content being 1.368 kg/m^2 and the thickness being 5 m. The lower limb has a grade of 0.0066%, with the uranium content being 1.0573 kg/m^2 and the thickness 7.6 m. The uranium orebody under the control of the drill core zk63-14 is 8.9 m in thickness, with a grade of 0.0108% and the uranium content being 2.0093 kg/m^2. The ore-host rock is grey conglomerate rock. The uranium orebodies under the control of No. 1 exploration line are complicated in shape. According to the characteristics of their spatial development, these uranium orebodies are referred to as multi-limb rolled uranium orebodies.

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