Late Cenozoic coal fires in Liuhuanggou area (Xinjiang, Northwestern China): Ages, controlling factors and evolution

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Abstract

Coal fires are a phenomenon that can be observed worldwide in areas where coal seams-bearing rocks are exposed and can pose major environmental threats. A coal fire can initiate through spontaneous combustion when coals are exposed to dry and oxygen-rich near-surface conditions. Burning, depending on the temperature of heating, causes baking or even melting of the surrounding rocks and results in the production of different types of combustion metamorphic rocks. In northwestern China, coal fires occurrences are concentrated at the edges of the sedimentary basins or at the margins of orogenic belts where coal-rich units were exposed due to the Indo-Eurasian collision. On the northern margin of Tianshan range, evidence of coal fires is widespread in the Jurassic coal seams-bearing sedimentary units cropping out along the Central Asian Orogenic Belt. In some cases, coal fires are active and can be linked to ongoing mining activity, but outcrops of combustion metamorphic rocks not associated to fires are also found and are indicative of past burning events. In this paper, we examine combustion metamorphic rocks outcropping in the Totunhe River valley (Liuhuangou area, Xinjiang, Northwestern China). Combustion metamorphic rocks in the study area were mapped and classified according to their morphological and mineralogical characteristics. Outcrops are exposed at various heights on the valley flanks that are characterized by the presence of multiple levels of fluvial terraces. These terraces are indicative of phases of erosion and deposition of the Totunhe River and testify for tectonic uplift. Investigation of stratigraphic and cross-cutting relationship of combustion metamorphic rocks with terrace deposits and apatite fission-tracks dating made it possible to determine that at least four phases of coal fire activity occurred, spanning from Late Miocene to Quaternary. The first and oldest burning phase dates back 10±1.3 Ma and terminated prior to 2-3 Ma; the second was active before ~550 ka; the third was terminated by ~140 ka; the fourth begun later than ~5.7 Ka. The relationships between combustion metamorphic rocks and fluvial terraces further suggests that coal fires ignition/extinction in the area since the Miocene could be linked to the interplay between the uplift of Central Asian Orogenic Belt and phases of fluvial erosion and deposition in interglacial periods.

Key Words: Late Cenozoic, coal fire, combustion metamorphic rocks, apatite Fission-Track dating, geomorphologic evolution

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1. Introduction

Coal fires are a phenomenon in which coal contained in sedimentary rocks ignites and then burns in the near surface for an indefinite time. Ignition may be natural (e.g. because of spontaneous combustion, forest fires, lightning strikes) or anthropogenic (e.g. because of mining activities) (Silva and Boit, 2011; Wang et al., 2003) and surface exposure of coal seams and therefore the availability of oxygen is considered a necessary condition for the development of a coal fire (Zhang et al., 2004). Coal fires are observed worldwide, such as in China, India, USA, Russia, and South Africa (Kuenzer and Stracher, 2012; Ribeiro et al., 2016; Song and Kuenzer, 2014; Stracher et al., 2015, 2007). Coal fires can in some cases represent a threat if significant emission of gases and particulate potentially dangerous for the environment and humans occurs (Kuenzer and Stracher, 2012; Song and Kuenzer, 2014, 2017; Stracher and Taylor, 2004).

Coal fires are common in northwestern China due to the abundance coal-bearing geological units. The ignition is favored by the intense quarrying activity of coal seams and by the arid climate conditions (Querol et al., 2008; Song and Kuenzer, 2014; Stracher and Taylor, 2004). Coal fires in northwestern China are particularly concentrated at the edges of the sedimentary basins (e.g., Ordos, Tuha, Yili, Tarim and Junggar Basins) or at the margins of orogenic belts (e.g., Tianshan Orogen) (Kuenzer et al., 2007; Sokol and Volkova, 2007). In these regions, the coal seams were exposed by uplift and erosion and this created the conditions for combustion.

Most studies have focused on the factors of spontaneous combustion of coals, and detection and extinguishing of modern coal fires (Hoffmann et al., 2003; Song and Kuenzer, 2017; Voigt et al., 2004). Less attention has been instead dedicated to the investigation of paleo-coal fires, although their existence is testified by the existence in the geologic record of combustion metamorphic rocks (a.k.a. pyrometamorphic rocks), i.e. rocks that were metamorphosed by heat generated by coal fires (Heffern and Coates, 2004). Combustion metamorphic rocks (CM) can be produced by heating and/or melting of rocks that host coal-fires and therefore are subjected to low- to high-temperature, low- pressure metamorphism. This process results in mineralogical modification caused by dehydration and/or oxidation that macroscopically can be testified by color and texture changes (Stracher et al., 2015). CM rocks are often relatively resistant to erosion and therefore can build morphological reliefs such as escarpments and terraces (Riihimaki et al., 2009; Heffern et al., 2007).

The ages of formation of CM rocks and therefore the time in which they were metamorphosed by active coal fires can be dated with zircon fission tracks, zircon (U-Th)/He dating or $^{40}Ar/^{39}Ar$ dating (Gur et al., 1995; Heffern et al., 2007; Novikov et al., 2008; Novikova et al., 2016; Sokol et al., 2014). $^{40}Ar/^{39}Ar$ dating of CM rocks in Central Asia, especially in the areas of Goose Lake Coal Basin and Kuznetsk Coal Basin has revealed that large-scale coal fires occurred in two stages, in the Early Pleistocene and Late Pleistocene (Novikova et al., 2016; Novikov et al., 2007, 2008, 2013; Sokol et al., 2014).

Along the northern margin of Tianshan mountain range, northwestern China, CM rocks are widespread (Novikov et al., 2007, 2013, Fig. 1B) and tend to form morphological reliefs units that were exposed by river erosion. This provides an unusual opportunity to study the ages and evolution of paleo-coal fires in the area. In this paper we present the ages of CM rocks in the Liuhuanggou area, Xinjiang Province through apatite fission tracks and investigate the time and possible cause effect relationship between the formation of CM rocks and the erosion/deposition history of the Totunhe River valley.

2 Geological setting

In China, the Tianshan Orogenic Belt extends more than 1700 km with a north–south width of 250 – 300 km (Fu et al., 2003; Wang et al., 2003). In response to the India - Eurasia collision during the Cenozoic (Delvaux et al., 2013; Dobretsov et al., 1996; Grave et al., 2007), the Tianshan belt has been one of the most active intracontinental mountain building belts in central Asia (Fig.1A, B) (Avouac et al., 1993; Fu et al., 2003; Glorie et al., 2016; Gong et al., 2015; Molnar and Tapponnier, 1975; Sun and Zhang, 2009). Therefore, the Mesozoic to Cenozoic sedimentary sequences in the northern piedmont of Tianshan belt have been intensely deformed (Avouac et al., 1993), forming three parallel rows of fold and thrust fault belts (Lu et al., 2010b). These three tectonic belts were termed as Belt I, II and III from the mountain front sequentially towards the Junggar Basin (Fig. 5), a larger forland basin in Xinjiang Province (Chen et al., 2010; Fu et al., 2003; Scharer et al., 2004; Sun and Zhang, 2009; Xu et al., 2015). The anticlines in the belts have approximately west-east striking axes, indicating a north - south compression (Gong et al., 2014). The study area is characterized by several rows of near NW - SE trending anticlines and syncline (Huang et al., 2016), including Kelazha Anticline, Akede Syncline and Toutunhe Syncline (Fig. 1C). Compressive faults are commonly seen in the Liuhuanggou are and torsional reverse faults mainly develop in the core of anticlines (Guo et al., 2007; Li et al., 2011b). In addition, several strike - slip faults are found in the study area (Li et al., 2011b). In the present study, the major section, Liuhuangou section, is located at the Kelazha Anticline and belongs to Belt I (43°42′40″N, 87°12′46″E) (Fig.1B, C). The study area is within the transition zone between Tianshan Mountain and Junggar Basin (Liu et al., 2017).

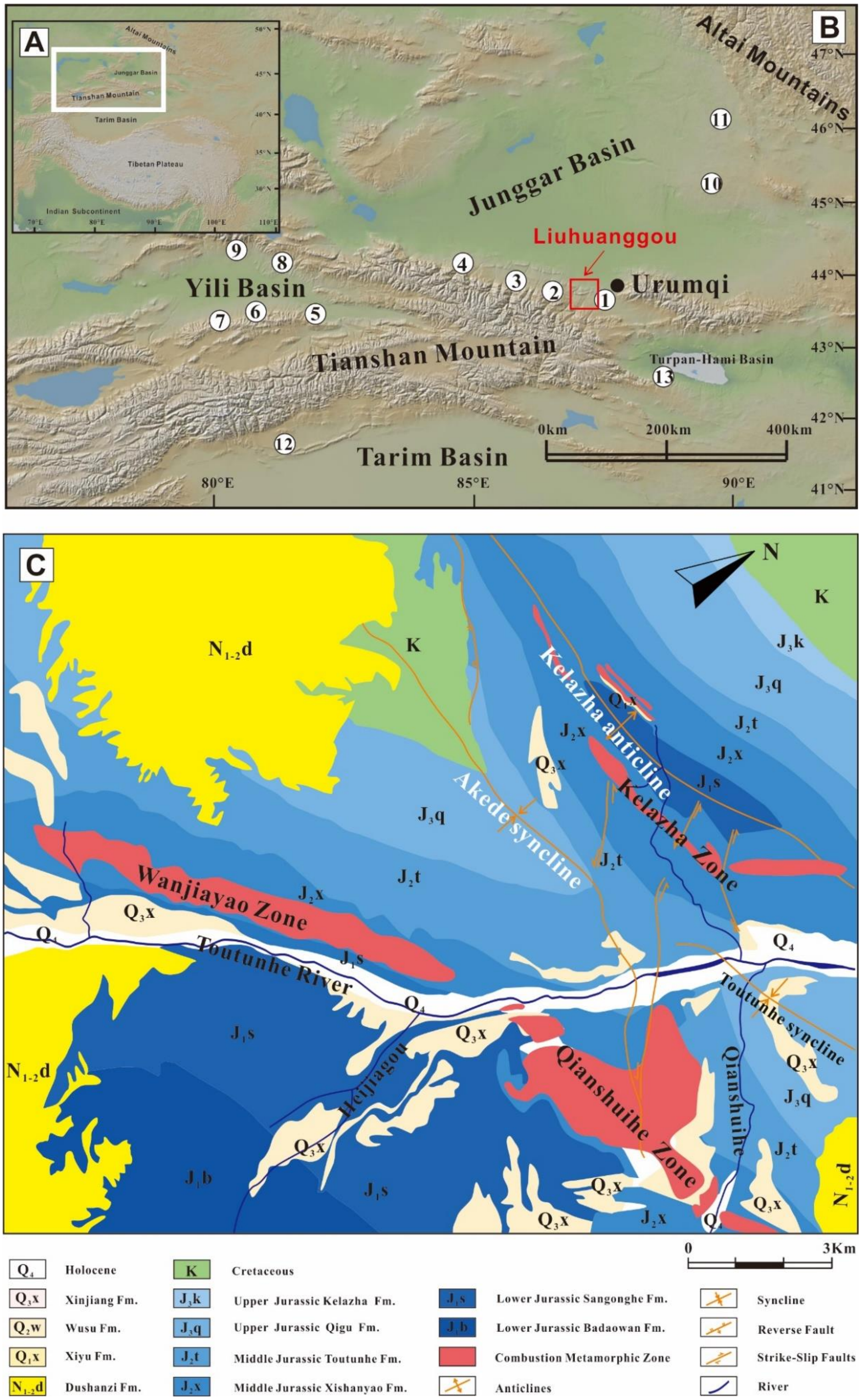

Fig. 1. (A)Topographic map of central Asia. (B) Location map of CM rocks and study

area in Northwest China. 1-4 Northern Tianshan piedmont; 5-9 Yili basin; 10-11 Eastern margin of the Junggar basin; 12 North margin of Tarim basin; 13 Turpan-Hami Basin, (Novikov et al., 2013, 2007). (C) Geological map of Liuhuanggou area showing the distribution of combustion metamorphic rocks (Guan et al., 1998; Li et al., 2011b).

Figure 1C shows a geological map of the study area. The coal-bearing sequences include the Middle Jurassic Xishanyao Formation and the Lower Jurassic Sangonghe and Badaowan Formations (Wu et al., 2012; Zhou et al., 2015). The main coal-bearing intervals are found in the lower Xishanyao Formation (Jiang et al., 2010; Li et al., 2016; Sun et al., 2012). The Jurassic and Cretaceous successions mainly outcrop in the Liuhuanggou area, unconformably covered by the Neogene and Quaternary deposits which are mainly found along the valleys of the Toutunhe River and its tributaries (Fig. 1C) (Kong et al., 2006; Fang et al., 2007; Zhang, 2015). The Neogene Taxihe Formation (N_1t) and Dushanzi Formation ($N_{1-2}d$) comprises fluvial facies (Li et al., 2011b). The Quaternary is represented by the Pleistocene Xiyu Formation (Q_1x), Wusu Formation (Q_2w), Xinjiang Formation (Q_3x). These units are mainly made of poorly cemented conglomerates of alluvial facies and the Xinjiang Formation typically forms fluvial terraces. Holocene alluvial deposits made of gravels, sands and loess represent the more recent infill of the river valley (Q_4) (Fu et al., 2003; 2017; Li et al., 2011b).

3. Methods

3.1 Field investigation and geomorphologic analysis

Field investigations were carried with Google Earth imagery and 1:80000 scale geological map (Guan et al., 1998). Based on the reconnaissance and geomorphological mapping, we mapped the distribution of CM rocks in the study area and identified fluvial terraces. Moreover, we identified the types of CM rocks based on petrology, which were reflected by mineral composition and the grade of thermal alteration.

3.2 Apatite fission-tracks dating

The CM rocks commonly had been heated to over 500℃ (Sokol and Volkova, 2007), and as a part of low-temperature thermochronology, apatite fission track dating is extremely sensitive to changes in temperature. Once the temperature of sample is over 120℃, the AFT age will be reset and record the thermal events, thus the application of this technique on CM rocks can represent the age of the coal fires that produced them (Heffern and Coates, 2004).

Two CM samples (S1 and S2) collected from the CM rocks outcropping in the study area. Location of the sampling locality is shown in Fig. 1C and Fig. 3A, B. Collected samples were crushed, and apatite grains were separated using heavy liquids and magnetic separation techniques, then were selected out under the binocular microscope. Mounts of apatite in epoxy were polished and then etched with 5 M HNO3 at 20 ℃ for 20 s. Samples were then irradiated in the well-thermalized reactor with a CN-5 dosimeter at the Radiation Center of Oregon State University (US). After irradiation induced fission tracks were revealed in the low-U muscovite detector by etched in 40% HF at 20℃ for 40 min. Apatite fission-track analyses were carried out under the a magnification of 1000 with dry objectives. The age calibration uses Durango standard with zeta value equal to 346.73±1.47.

4. Results

4.1 Characteristics and distribution of combustion metamorphic rocks in the Liuhuanggou area.

Types of CM rocks identified in the study area are clinkers (Fig. 2A-C), porcellanites, (Fig. 2E) and paralavas (Fig. 2F-G). All CM rocks are characterized by multicolored glassy porcelain or brick like appearance.

Clinkers were baked at a relatively low temperature. They were mainly found in the Kelazha area, and the most distinguishing feature of clinker is its red color (Figs. 2A-C). Porcellanites are commonly found in contact with clinkers. They are dense, hard, partly or completely sintered clays of porcelain-like appearance (Fig. 2E). Paralavas, completely fused rocks, are mainly distributed in both sides of Qianshuihe river. Paralavas also lie directly above the coal ash in the form of thin veinlets or occur as cement fragments of vitreous clinkers called combustion metamorphic breccias (Figs.

2F-G).

CM rocks are found along the Toutunhe River or exposed on topographic scarps. In addition to the CM rocks, some other products linked to coal spontaneous combustion that can be found in the study area are gas-vent minerals (e.g. Sulphur, Sal ammoniac, Fig. 2F), coal tar, coal ash layers (Fi g. 2D)

Three main CM rock areas have been identified: Wanjiayao Area, Qianshuihe Area and Kelazha Area (Fig. 1C).

The Wanjiayao Area is located in the upper reaches of the west bank of Toutunhe River and is elongated along the fluvial terraces (CM-4, Fig. 3). The length is about 7.5 km, the width is about 0.42 km. Due to coal seams combustion, a large number of subsidence fissures are formed on the surface, and some fissures directly communicate with the lower coal seam. These cracks promote combustion by permitting oxygen to circulate to burning coal in the subsurface.

The Qianshuihe Area is located in the east bank of the Toutunhe River (including CM-2, 3, 5 and 6). The CM rocks is widely distributed on a surface of approximately 7.02 km^2 (Fig. 1C). The distribution of CM rocks is related to fluvial terraces (Fig. 3).

The Kelazha Area is located in the two limbs of the Kelazha Anticline (including CM-1 and 7, Fig. 1C). CM-1 is located on the north wing of Kelazha Anticline, and the CM rocks mainly distribute near the steeply dipping. CM-7 is located on the other wing of the Kelazha Anti. White smoke is visible and some minerals nucleated along cracks and vents of CM rocks.

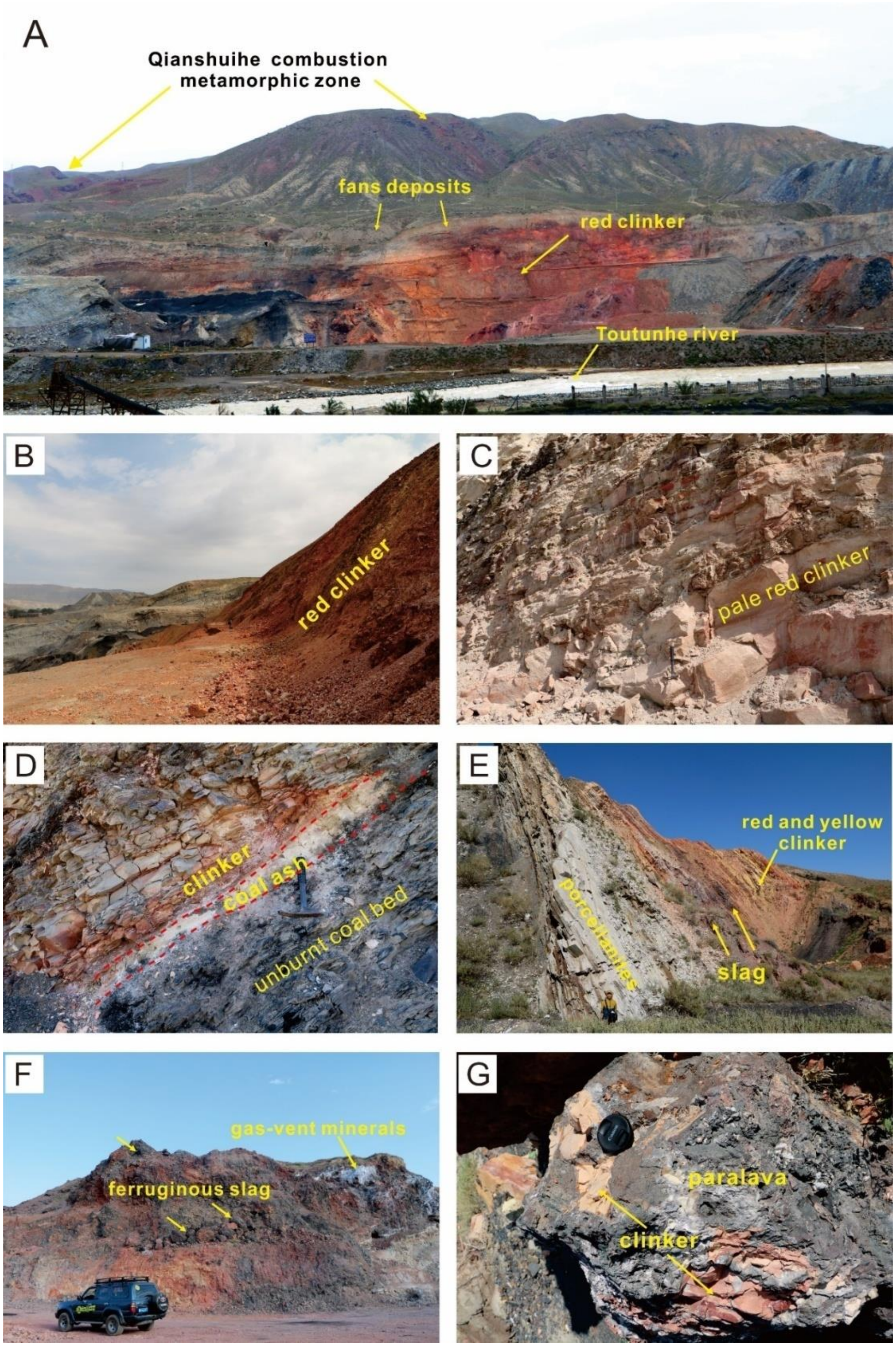

Fig.2. Macrophotograph of combustion metamorphic rocks. (A-C) Clinker converted to red and pale red due to spontaneous combustion of the coal in the Qianshuihe combustion metamorphic area. (D) Unburnt coal bed near the bottom of the photo, coal ash in the middle, clinker in upper part. (E) Clinker, slag and porcellanites in Kelazha combustion metamorphic area. (F) Ferruginous slag formed during the spontaneous

combustion of coal beds. (G) combustion metamorphic breccias, red clinker fragment cemented by massive black paralava.

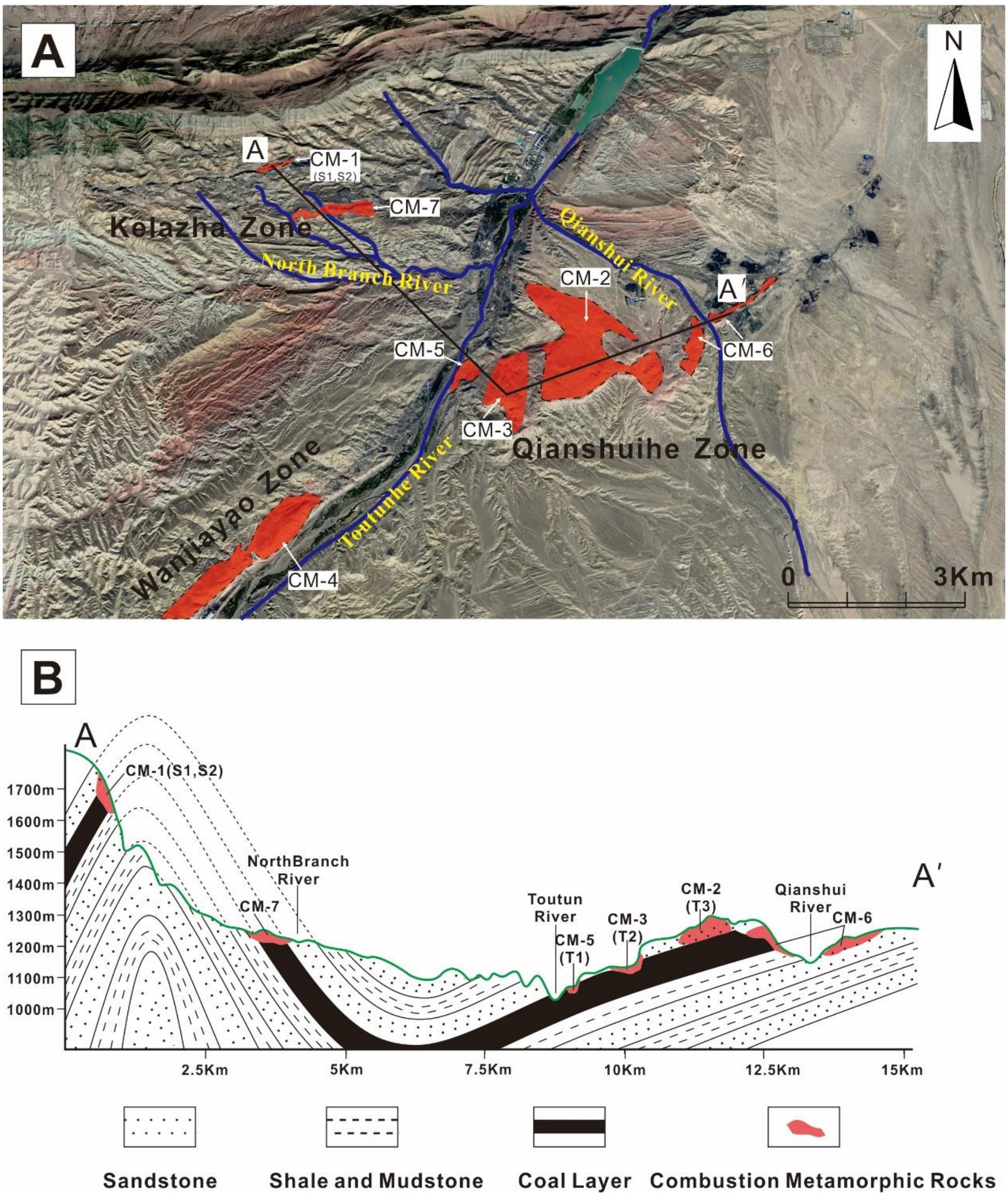

Fig.3. (A) The distribution of CM rock outcrops (CM-1 – CM-7) on Global Mapper of Liuhuanggou area. (B) Cross section(A-A′) across Toutunhe River (Terrain data from Global Mapper), showing CM rocks outcrops, coal beds and fluvial terraces (T1 – T3).

4.2 Apatite fission tracks

Our apatite fission track ages (S1 and S2) show a small range from 5 Ma to 24.5 Ma with central ages 10 ± 1.3 Ma and 9.8 ± 1.4 Ma (Fig.4). The $\chi 2$ probability P ($\chi 2$) = 0.78

and 1, and this indicates that the samples contain a rather homogeneous age population and apatite grains underwent annealing because of the same event.

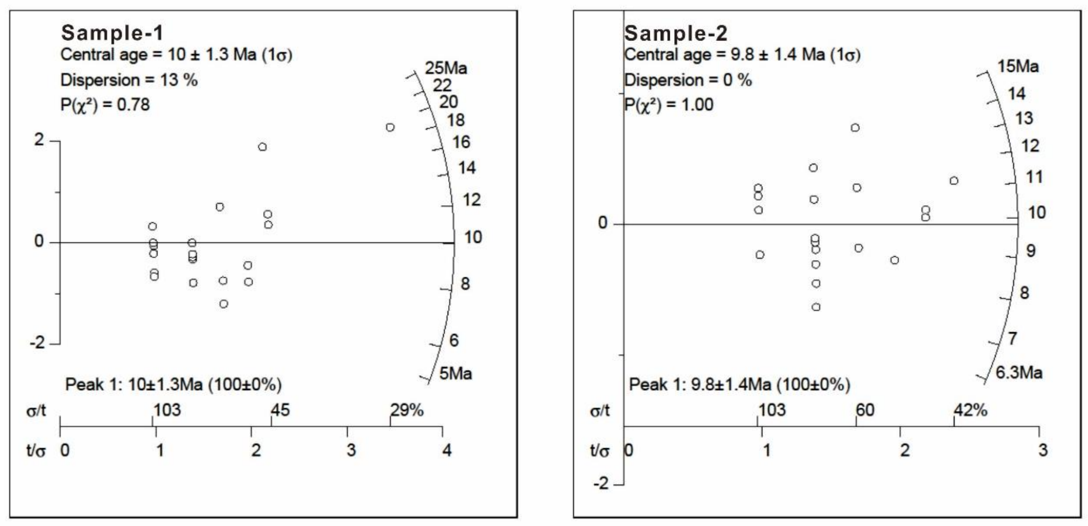

Fig.4. The radial plot of AFT ages

5. Discussion

5.1 Control factors of spontaneous combustion of coal seams

As exposure of coal seams is needed to create conditions for the ignition of coal fires (Novikova et al., 2016; Reiners et al., 2011; Riihimaki et al., 2009; Sokol et al., 2014), understanding the age of tectonic uplift and erosion history in Liuhuanggou area, can help to constrain the time of spontaneous combustion phases.

5.1.1 Tectonic uplift

The Tianshan range uplift is related to the India- Asia collision that led to intense structural deformation and erosion (Molnar et al., 1993; Tapponnier et al., 2001). The onset of the uplift of the Tianshan range has been dated between 10 and 7 Ma (Charreau et al., 2005; Fang et al., 2007; Ji et al., 2008; Li et al., 2011b). Magnetostratigraphic studies and stratigraphic relationships suggest that the formation of folds and thrusts occurred roughly between the Miocene and the early Pleistocene (Daëron et al., 2007; Fu et al., 2017; Sun and Zhang, 2009; Sun et al., 2004). Furthermore, Li et al. (2011a, 2011b) suggested that the uplift ages become younger from south to north and therefore a relative age can be attributed to structural Belts I to III, being Belt I the oldest and

Belt III the youngest. Based on the field research and seismic interpretations, Guo et al., (2006) and Chen et al., (2007) suggested that the uplift time of Belt II and Belt III occurred after the deposition of Xiyu Formation. The age of the Xiyu Formation was determined at about 2.58 Ma through magnetostratigraphy (Charreau et al., 2009; Sun et al., 2004). Li et al. (2011b) inferred that the accelerated folding of the anticlinal belts at approximately 2Ma for Belt II (Tugulu Anticline) and about 1Ma for Belt III (Anjihai Anticline), according to identified growth strata dated with existing magnetostratigraphy, together with balanced cross sections from interpreted seismic data. Fang et al. (2007) and Li et al. (2011a) suggested that the intense uplift and structural deformation of Kelazha Anticline (the location of the study area, belonging to Belt I) began in the middle-late Miocene based on the studies of growth strata of Changjihe Group.

5.1.2 Ages of fluvial terraces

The age of fluvial terraces in the valleys of the Tianshan range has been extensively studied (Table. 1) using optically stimulated luminescence (OSL) or electron spin resonance (ESR) (Fu et al., 2017; Lu et al., 2014; Yang et al., 2013). The age of the terraces testifies a connection between their genesis and the uplift of the structural Belts as older terraces are found in Belt I and their age gets younger through Belt II and Belt III. This is likely due to incision and deposition linked to the uplift phases. Although fluvial terraces in our study area have not been directly dated, ages for terraces in the nearby Urumqi River (Fig. 5) valley are available. There, three terrace levels have been identified and assigned an age through dating of the terrace sediments by OSL and AMS^{14}C from at about ~5.7 ka (lower and youngest terrace level), ~140 ka (intermediate terrace level) and ~550 ka (upper and oldest terrace level) (Lu et al., 2014; Zhou et al., 2002).

In analogy to what is observed in the Urumqi river valley, our field investigations allowed the identification of three levels of terraces associated to alluvial fans in the Toutunhe River valley (Fig. 3). From the lowest (i.e. younger) to the highest (i.e. older) we named them T1 (terrace level 1), T2 (terrace level 2), T3 (terrace level 3). Given the vicinity of the two valleys and since both of them are located in structural Belt III, the oldest in the Tianshan range, it is reasonable to assume that the three generation of terraces in the two valleys belong to the same phases of incision/deposition and therefore can be assigned roughly similar age. Therefore, T3 is assigned an approximate age of 550 ka, T2 an approximate age of 140 ka and T1 an approximate age of 5.7 ka.

The formation of fluvial terraces is generally due to the vertical incision of river caused by tectonic uplift (Yang and Li, 2005). Climatic fluctuations during glacial–interglacial transitions can induce the formation of fluvial terraces. Deposition and aggradation of fluvial deposits may occur in the late phases of glacial cycles, while the incision that shapes the terraces may happen near to glacial–interglacial transitions (e.g., Bridgland, 2000; Lu et al., 2010a and 2014). Advances and retreats of glaciers in study area is testified by five sets of Quaternary moraines. These moraines have been attributed to Little Ice Age (~1500 – 1900), Neoglacial (~4 – 7 ka), Shangwangfeng (~20 – 40 ka), Xiawangfeng (~60 – 75 ka for the upper part and ~130 – 190 ka for the lower part), and Gaowangfeng (~470 ka), respectively (e.g. Xu et al., 2010; Zhao et al., 2006). The age of fluvial terraces allows to roughly refer them to these glacial stages: T3 is approximately coincident with Gaowangfeng stage, T2 with Xiawangfeng stage and T1 s with Neoglacial stage (Lu et al., 2014; Fig. 8).

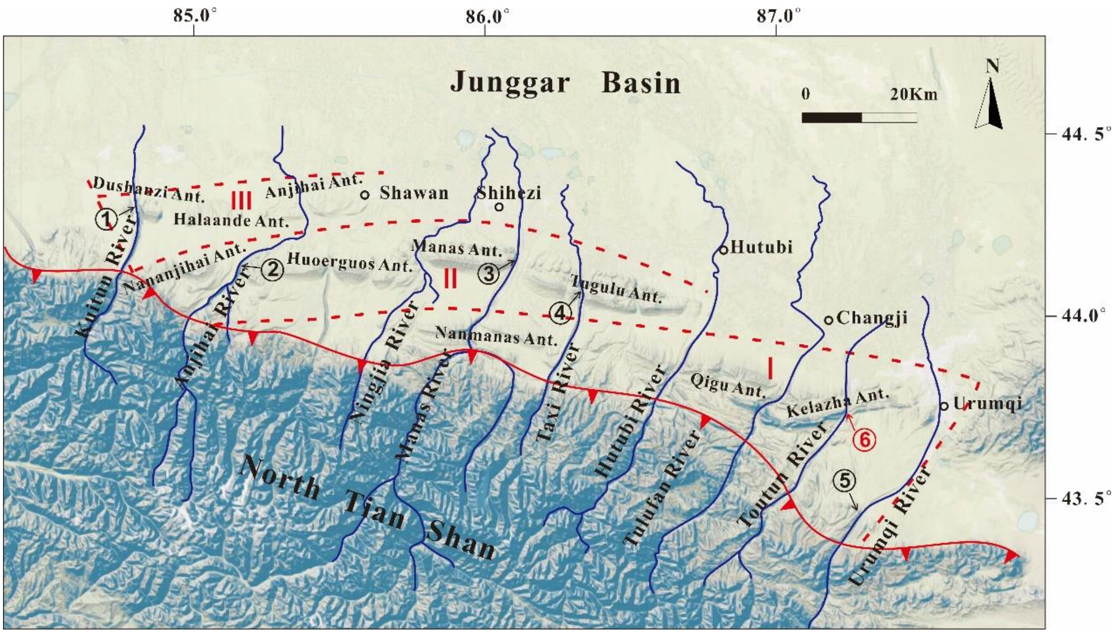

Fig. 5. Topographic map of the northern Tian Shan foreland, where three structural Belts

(I, II, and III) characterize the regional topography. Numbers (1 - 6) indicate the sections.

Table 1: A comprehensive overview of the formation ages of fluvial terraces in northern Tian Shan piedmont.

River	Section	Tectonic zone	Anticline	Age of fluvial terrace(Ka)			References
				I	II	III	
Kuitun River	①	III	Dushanzi Ant.	14.98	29.3-39.2	58-75	(Yang et al., 2013)
Anjihai River	②	III	Anjihai Ant.	3.6±0.1	9.0±0.6	53.3±2.2	(Fu et al., 2017)
Manas River	③	II	Manas Ant.	11.97	30.74	＞31	(Yang et al., 2013)
Taxi River	④	II	Tugulu Ant.	10	300	530	(Lu et al., 2010a)
Urumqi River	⑤	I	Saerqiaoke Ant.	3.9±0.45	142±14(T5)	550	(Lu et al., 2014)
Toutunhe River	⑥	I	Kelazha Ant.	5.7	～140（Refer to Urumqi River）	～550（Refer to Urumqi River）	This study

5.2 Ages of coal fires

Apatite Fission-Tracks on CM rocks, estimates of the ages of tectonic uplift and fluvial terraces and the stratigraphic relationship between CM rocks and the overlying sediments can provide time constraints on the activity of coal fires in the study area. According to the spatial distribution characteristics of the CM rocks and the relationship with the fluvial terraces, we divided the three combustion metamorphic zones in the study area into seven CM rocks distribution areas, named CM-1 to CM-7 (Fig. 3).

CM-1 is located in the Kelazha Area, north limb of Kelazha Anticline (Fig. 3), 7.5Km from Toutunhe River and 600 m above the Toutunhe River. The CM rocks mainly distribute near the steeply dipping exposed coal seam (Fig. 6A), extending along the anticline strike and covered by the conglomerate of Xiyu Formation (Q_1x). These latter do not show evidence of metamorphism (Fig. 7A) (Chen et al., 1994; De Boer, 1999; Sun et al., 2004; Zhang et al., 2004). Given the age of the Xiyu conglomerates (~2-3Ma in the Taxi River section, Li et al., 2011a; Sun and Zhang, 2009) and the fact that the conglomerates are not metamorphosed, the coal fires that produced CM-1 was active before prior to ~2-3Ma.

Apatite Fission-Track ages retrieved from samples from CM-1 range from 5 Ma to 24.5 Ma with central age at 9.8±1.4 and 10±1.3 Ma (Fig. 4). They are much younger than depositional age (Middle Jurassic), indicating our samples are reset or significantly annealed. Hence, the central ages at ~9.8-10 Ma can be considered an estimate of the time in which that coal fire was burning. Moreover, these ages are consistent with the ages of formation of the Kelazha Anticline (Fang et al., 2007; Li et al., 2011a, Fig. 8). We therefore propose that the coal fires of CM-1 were active during late Miocene-Pliocene when uplift produced the structural Belt I and brought to the surface the coal seams in the Xishanyao Formation, but extinguished before 2-3 Ma, i.e. before the deposition of the Xiyu Formation conglomerates.

CM-2 is located on the Qianshuihe Area with an altitude 1250m, 120m above the Toutunhe River. CM-2 is located in correspondence of the highest, and therefore oldest, fluvial terrace (T3) (Fig. 3). Fluvial terrace sediments overlying the CM rocks are not metamorphosed (Fig. 7B). This means that the deposition/incision phase that formed the terrace occurred when those CM rocks were already formed and therefore the coal fire responsible of their formation is older than the deposits that make up the terrace. The age of the T3 terrace is estimated to be 550ka (Table 1), therefore the age of CM-5` coal fire is older than 550 ka.

CM-3 rocks are exposed in the second terraces (T2) of Toutunhe River (Fig. 3), 100m above the Toutunhe River. The CM rocks are mainly red clinker and black paralavas with a thickness of 20-25m (Fig. 6B). Also in this case, the overlying fluvial terrace sediments show no signs of heating, but contain CM rocks clasts (Figs. 6B, 7C）. As the river sediments covering CM-3 are not metamorphosed and the age of the second terrace (T2) has been estimated at about 140ka (Table 1) the coal fire connected to CM-3 is older than 140 ka and extinguished before the deposition of T2 fluvial deposits.

CM-4, in the Wanjiayao Area, is located on the west side of the upper reaches of the Toutunhe River (Fig. 3), 100m above valley bottom. The situation is the similar to combustion rocks of CM-3 as products of coal fire burning are exposed in the second fluvial terrace level (T2), and the sediments making up the terrace are not metamorphosed. Therefore, also in this case the combustion phases of CM-4 can be considered older than 140 ka.

CM-5 is located on the east bank of Toutunhe River and crops out in the scarp of first terrace level (T1), 40 m above the Toutunhe River (Fig. 3) River. The CM rocks are mainly red clinker layers with ferruginous nodules (Fig. 2B). The thickness of the clinker varies from 50m-100m. The overlying Holocene alluvial deposits (Q_4) (Poisson and Avouac, 2004) is in this case show signs of metamorphism (Fig. 6C, 7D). This indicates that coal fires of CM-5 begun burning after the deposition of Holocene sediments (i.e. after the formation of fluvial terraces of T1). Since the age of the first terrace (T1) of the Toutunhe River is 5.7Ka (Table 1), the CM-5 coal fires activity phase is younger than 5.7Ka.

CM-6 is distributed on both sides of the Qianshuihe River, which is the tributary of the Toutunhe River (Fig. 3). It is mainly composed of black paralavas and some gas-vent minerals (e.g., sulfur, salammoniac).

CM-7 is located on the west of Toutunhe River, 180m above the Toutunhe River, and distributed on the both sides of North Branch River (Fig. 3). A large amount of white smoke is visible in CM6 and CM7, and minerals such as sulfur, gypsum and calcite nucleated along cracks and vents, indicating that the coal fires are recent.

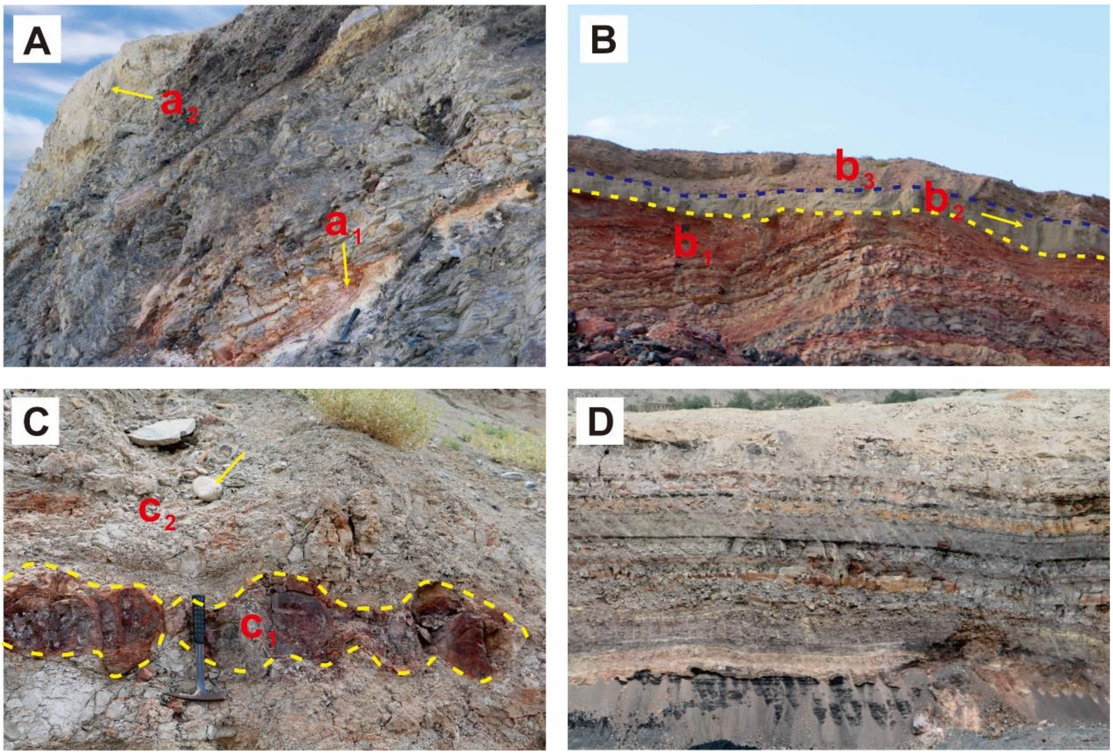

Fig.6. Appearance of combustion metamorphism rocks. (A) Located in CM-1, a_1: red clinker, a_2: overlying sediment. (B) Macro photo located in CM-3, the red and black clinker have been deformed and converted due to combustion of the coal below, and overlying terrace deposits. b_1: combustion metamorphism rocks, b_2: terrace deposits that are not baked by coal fires, b_3: gravel layer containing the CM rocks as the uppermost layer. (C) Located in CM-5, c_1: Ferruginous nodules and layers, c_2: The terrace deposits that are affected by high temperatures. (D) Modern coal seam combustion due to mining.

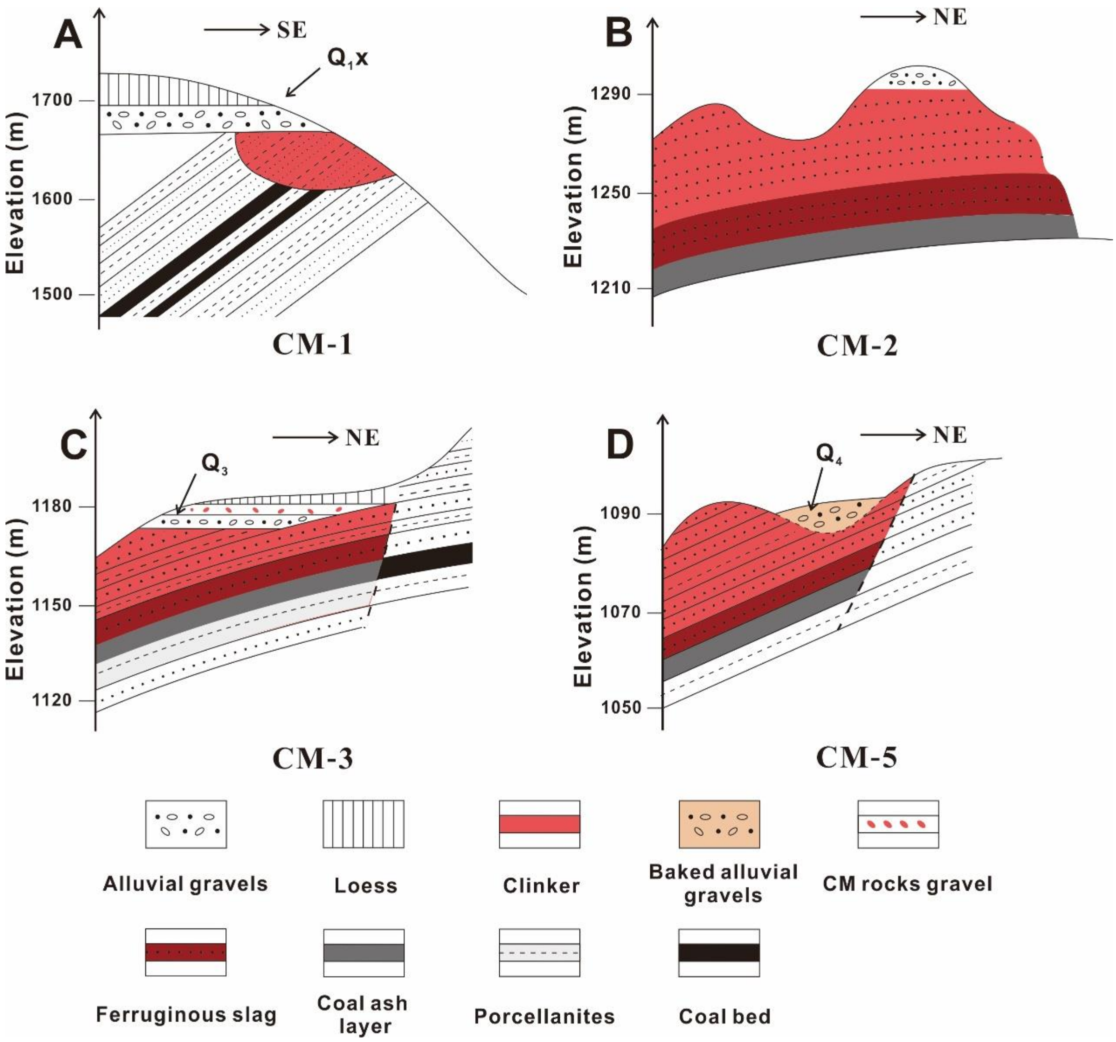

Fig.7. The profile showing the contact relationship between CM rocks and overlying fluvial terrace sediments.

In summary, the study area has experienced five phases of coal seam combustion (Fig. 8): the first phase combustion occurred in the CM-1 area during the Late Miocene, and ended before the Pleistocene (i.e. before the deposition of the Xiyu Formation). With the erosion of Toutunhe River, three other phases of paleo-coal fires (CM-1, CM-3/CM-4 and CM-5) activity occurred in the Quaternary in turn. The final burning phase is in the CM-2 and CM-6 due to the present mining engineering.

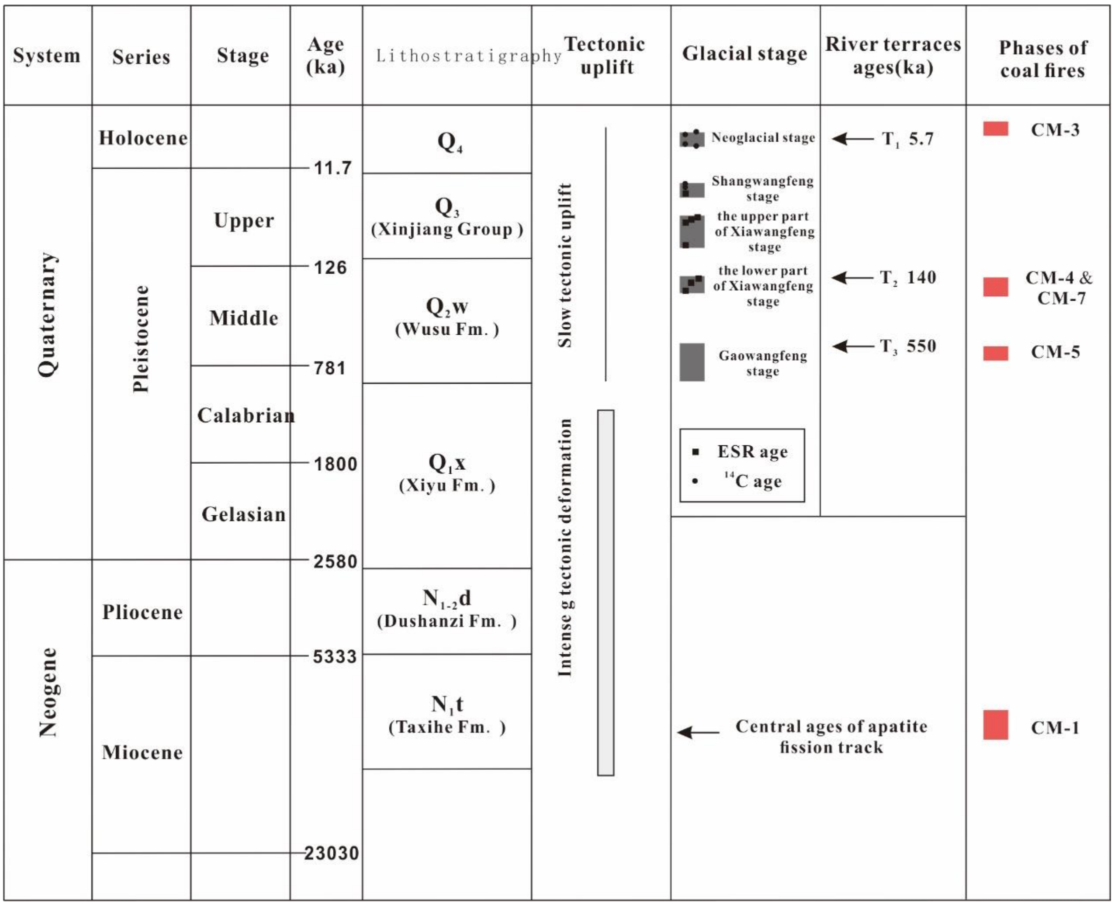

Fig.8. The phases of combustion events. Stratigraphic chart (Fu et al., 2003). Glacial stage (Xu et al., 2010; Yi et al., 2004; Zhao et al., 2006). Fluvial terraces age (Lu et al., 2014).

5.3 Evolution of paleo-coal fires

The evolution model of coal fires in the Liuhuanggou area is shown in Fig. 9. In the Late Miocene, the Kelazha Anticline formed and was eroded (Fang et al., 2007; Li, et al., 2011b), causing exposure of coal seams to oxygen and created the necessary conditions for combustion. At CM-1, through the apatite fission track data and contact relationship of overlying sediments, we propose that coal seam combustion was active at about 9.8-10 Ma and extinguished before the Pleistocene (Fig. 9A).

Since the Middle Pleistocene, progressive incision of Toutunhe River exhumed coal seams that are now outcropping at different heights on the valley's flanks. The first that were exhumed were likely those that now occupy the highest elevation: pyrometamorphic rocks if CM-2. The fact that CM-2 rocks were covered by the T3 terrace alluvial depositsand that these deposits do no show evidence of heating suggests that the coal fires were already extinguished when they deposited (Fig. 9B).

Progressive incision of the valley further exposed coal seams bearing rocks. Coal fires again sparked and the pyrometamorphic rocks of CM-3 formed (Fig. 9C). A new episode of alluvial deposition at approximately 140 ka brought to the accumulation of the conglomerates forming T2 terrace. Also in this case no sign of metamorphism is found in the sediments above CM-3 rocks, indicating that coal fire was already extinct when they deposited and were incised forming T2.

A further episode of incision brought to exposure of coal seams at lower elevation. Ignition again occurred and coal fires developed and the pyrometamorphic rocks of CM-5 were formed (Fig. 9D), however in this case the alluvial deposits overlying them and forming T1 terrace do display evidence of metamorphism. Hence, in this case we have the evidence that the coal fire was still active when the fluvial gravels of T1 deposited or it started burning after their deposition. This allows bracketing the activity phase of this coal fire between 5.7 ka and present time.

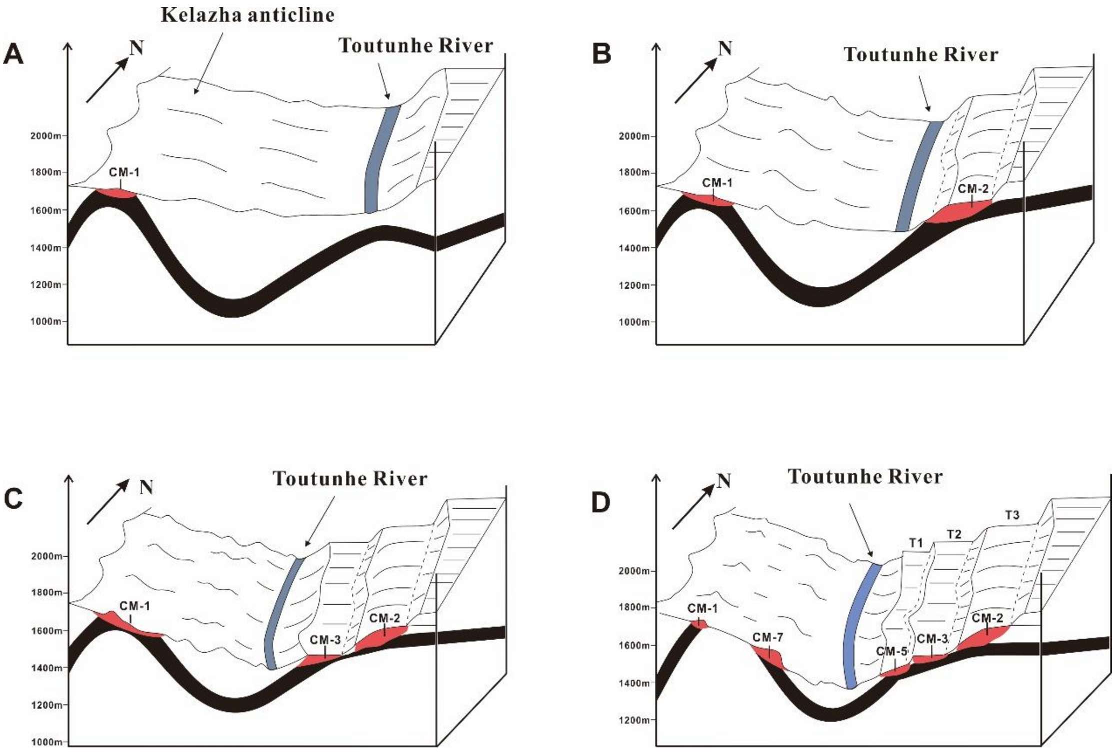

Fig.9. Evolution model of spontaneous combustion in coal seam.

6 Conclusions

The investigation and analysis of combustion metamorphic rocks in the Liuhuanggou area was carried out show the closer correlation between the coal fires and exposing conditions caused by tectonic uplift and river down cutting in the Liuhuanggou area. Based on the Apatite Fission-Track dating combustion metamorphic rocks, the ages of tectonic uplift and fluvial terraces and contact relationship with the sediments overlying the outcrops of pyrometamorphic rocks allow reconstruct four phases of coal fire activity spanning from Late Miocene to recent. An evolution model that explains how the interplay between uplift, river incision/deposition brought to the progressive exposure of coal-bearing units creating the conditions for the spontaneous ignition of coal fires.

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