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中亚造山带中的燃烧变质事件及其年代学研究*

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Novikov IS and Sokol EV. 2007. Combustion metamorphic events as age markers of orogenic movements in Central Asia. *Acta Petrologica Sinica*, 23(7):1561 – 1572

Abstract Combustion metamorphic (pyrometamorphic) complexes produced by prehistoric natural coal fires are widespread in Central Asia, namely at the interfaces between mountain systems and the flanking sedimentary basins. Large-scale and prolonged fires accompanied the initial orogenic stages as unweathered coal-bearing formations became exposed into the aeration zone. Pyrometamorphic rocks are comparable to sanidinite facies rocks in formation conditions and in alteration of sedimentary material but, unlike these, their protolith underwent different melting degrees to produce either ferrous basic paralavas or glazed clinkers. The phase composition of the newly-formed melted rocks are favorable for $^{40}Ar/^{39}Ar$ dating of combustion metamorphic events which are coeval to the onset of the main stage of recent orogenic events. We suggest a new algorithm providing correct $^{40}Ar/^{39}Ar$ dating of pyrometamorphic rocks followed by well-grounded geological interpretation. We studied pyrometamorphic rocks in the western Salair zone of the Kuznetsk coal basin where combustion metamorphism under temperatures above 1000℃ acted upon large volumes of coal-bearing sediments. Samples of paralavas were dated by the step heating $^{40}Ar/^{39}Ar$ method checked against internal (plateau and isochrone ages) and external ("criterions of couple") mineralogical criterions, and against preliminary dating from geological and stratigraphic evidence. As a result, we distinguished two groups of dates for combustion metamorphic events. The first one (1.2 ± 0.4Ma) is drawn towards the west boundary of Prokopyevsk-Kiselevsk block of Salair zone, while the second one (0.2 ± 0.3Ma) is confined to its east boundary. The former ages represent rocks in the western edge of the Prokopievsk-Kiselevsk block of the Salair zone and the latter ages correspond to those in its eastern edge. The dates record the time when the fault boundaries of the blocks were rejuvenated during recent activity and the block accreted to the Salair orogenic area as a piedmont step. These are the first absolute ages obtained for the onset of uplift of the northern edge of the Altai-Sayan area, the key event of its neotectonic history. The suggested approach to the choice of objects, classification of rocks, and interpretation of $^{40}Ar/^{39}Ar$ data is universal and can be practiced in any area subjected to combustion metamorphism.
Key words Geochronology, $^{40}Ar/^{39}Ar$ dating, Neotectonics, Combustion metamorphic complexes, Paralava, Clinker, Kuznetsk basin, Altai-Sayan area.

关键词 同位素年代学; $^{40}Ar/^{39}Ar$ 定年; 新构造; 燃烧变质杂岩; 似熔岩; 接触变质煤; Kuznetsk 盆地; Altai-Sayan 地区
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1 Introduction

The ages of Cenozoic orogenic events in the Altai-Sayan area were constrained until recently by stratigraphic evidence of the neotectonic stage since the latest Paleogene and rapid acceleration of movements in Neogene-Quaternary time (Devyatkin, 1970). The available isotope ages were obtained for basalts from the East Sayan, Hangayn, and Gobi Altai mountains, but basaltic eruptions there had no direct linkage to orogenic events. The commonly used age markers in these basaltic provinces are Late Jurassic, Cretaceous, Paleogene, Neogene, and Quaternary lavas (Devyatkin, 1981; Glukhovskaya, 1990; Yarmolyuk *et al.*, 1994; Zhu *et al.*, 2005, 2006; Zhu and Xu, 2006), which indicate the time of

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the latest activity by their position relative to modern landforms. Late Cretaceous, Paleogene, and locally Early Neogene basalts armor the preorogenic peneplain while Late Neogene and Quaternary lavas fill river valleys. This pattern generally supports the stratigraphy-based sequence of recent orogenic events.

On the other hand, a large part of the Altai-Sayan area lacks young volcanics. The onset of the main stage of the latest orogeny in the area was timed against the appearance of red coarse detrital molasse in piedmont aprons. The molasse was assigned a Late Neogene (pre-Pleistocene) age proceeding from the idea that redbed deposition in Central Asia ceased after cold and dry climate had set up in the Pleistocene. This approach, however, bears a vicious circle, as mountain-growth is associated with cooling, while the latter is attributed to glaciation during mountain growth (Molnar and England, 1990). Thus the lack of reliable age markers limited the possibility to time recent tectonic events in the large Altai-Sayan area, which is absolutely necessary for geodynamic reconstructions.

We found these markers, suitable for $^{40}Ar/^{39}Ar$ dating, among pyrometamorphic (combustion metamorphic) complexes consisting of rocks produced by natural burning of coal beds at early stages of large orogenic events within the deformed periphery of piedmont basins. Pyrometamorphic rocks occur in the surroundings of young mountains worldwide. In Central Asia they exist along the periphery of the Tien Shan (Jonggar, Fergana, and Issyk-Kul basins), in the Pamir-Alai mountains, and in the Kenderlyk and Kuznetsk basins (Saidov, 1956; Sokol *et al.*, 2005). We found combustion complexes in the Chuya basin in Gorny Altai (Fig. 1).

In situ coal seams cannot burn for the lack of free oxygen, and combustion becomes possible only when they get into the aeration zone. Progressive involvement of basin periphery into uplift during mountain growth occurred in all recent mountain terrains of Central Asia, including the Altai-Sayan area (Novikov, 2004). According to morphotectonic data, coal-bearing basin fill becomes involved in uplift in several stages. First, narrow plates become pressed out upward and then the entire strip they cut off rises to form piedmont steps. Thereby the rocks become exposed to aeration above the groundwater level, experience tectonic stress associated with crushing and degassing of coal, and become cut by gullies. This creates the prerequisites for large-scale combustion of coal beds into high-temperature paralavas and clinkers. Today clinkers and paralavas have been thoroughly investigated in the Kenderlyk basin (Kalugin *et al.*, 1991). Basic paralavas produced by underground coal fires have a particular chemistry but are very much alike the common basalts, and are often attributed to Cenozoic eruptions.

We tested the new approach to dating neotectonic events from products of combustion metamorphism of sedimentary protolith in the Kuznetsk basin. We selected this sample area because it is the largest and best-documented coal basin in West Siberia, with a unique pyrometamorphic complex along the basin western edge, which is moreover well exposed and easily accessible.

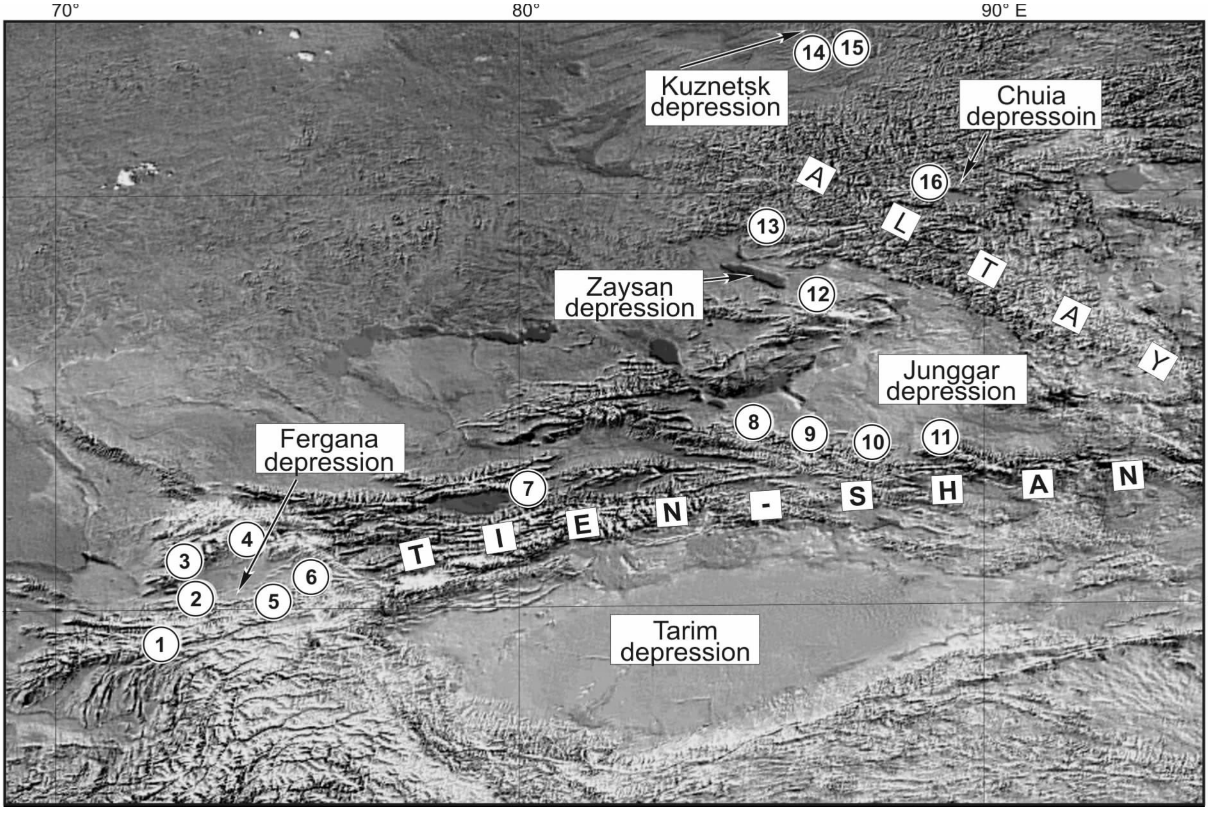

Fig. 1 Location map of pyrometamorphic complexes in Central Asia. 1-Ravat Fire (Tajikistan); 2-Sulyukta (Kyrghisia); 3-Angren (Uzbekistan); 4 ~ 7-Tash-Kumyr, Kyzyl-Kii, Kok-Yagnak, Jergali (Kyrghisia); 8 ~ 11-pyrometamorphic complexes of northern edge of the Chinese Tien Shan (China); 12-Kenderlyk (Kazakhstan); 13-Narynvalley (Kazakhstan); 14, 15-Kuznetsk basin (Russia); 16-Chuya basin (Gorny Altai, Russia)

2 Geological and tectonic framework of the Kuznetsk basin

Systematic studies of the Kuznetsk coal basin began in the 1890s by geologists from the Geological Department of the Russian Emperor's Office, as it was a property of the royal family. After the land was allotted to the state property, studies continued in 1914 by L. I. Lutugin, a noted expert in the geology of the Donetsk coal basin (Ukraine), and his disciples P. I. Butov and V. I. Yavorsky (Butov and Yavorsky, 1922). The coaliferous fill of the Kuznetsk basin, exceeding 10km in total thickness, lays without evident angular unconformity but with a stratigraphic gap over Lower Carboniferous eroded marine limestone and mudstone. The accumulated sediments were first eroded during a brief uplift episode and then the following basin-floor subsidence was compensated by deposition. Rock lithologies and fauna evidence indicate deposition in a shallow brackish sea which gradually became freshwater. The marine conditions gave way to lagoonal and then wetland environments. Subsidence kept up by deposition lasted as long as the latest Late Permian. The Triassic was the time of erosion and local deposition of continental volcano-sedimentary formations. Sediments in the middle of the Triassic section host three basaltic sills. Marine deposition in the Jurassic and Early Cretaceous was restricted to few localities. In the Cenozoic the area was no longer a sedimentation basin, and fluvial, slope-wash and mainly loess deposition occurred only locally on divides. The Late Paleozoic-Mesozoic coal-bearing sediments belong to several formations jointed into four large groups: Permian-Carboniferous Balakhon, Late Permian Kolchugino, and Triassic Maltsevo groups, and a Jurassic group of conglomerates.

Early studies in the 1920s already showed that the sediments of the Kuznetsk basin periphery were first complexly folded and then cut by a system of repeatedly rejuvenated normal faults (Yavorsky and Butov, 1927). Yavorsky and Butov were the first who noted that both folding and faulting decay toward the basin center and that the peripheral normal faults make up a staircase system clearly expressed in the surface topography. The most strongly deformed rocks belong to the Balakhon Group in the lower sedimentary section exposed along the basin periphery. Deformation is especially intense in the Salair part of the basin, in the Prokopievsk-Kiselevsk area, where folds are strongly compressed, often have their limbs overturned basinward, and are dissected by numerous reverses and thrust faults. The Kuznetsk basin borders the flanking mountains mainly along reverse or thrust faults dipping off the basin. The basin axial part is less deformed, with scarcer faults and Triassic and Jurassic deposits folded into broad shallow-dipping synclines. Unlike the Donetsk basin in the Ukraine, the Kuznetsk basin was not itself subject to folding but experienced horizontal pressure from the neighbor fold structures, especially the Salair and Kuznetsk Alatau ridges (Korovin, 1941).

The geology of the Kuznetsk basin, as well as most sections in large intermountain basins of Central Asia, bears signature of three major orogenic stages of the continental evolution. In the course of its history, the basin was a plunge, which stored the record of mountain growth in its fill and, more so, was itself deformed in the periphery. Being folded and involved into uplift, the basin became about 21% shorter in the W-E dimension, according to estimates by Yavorsky (1948).

3 Geology and geomorphology of the Salair zone

The landscape of the Salair zone (Prokopievsk-Kiselevsk area) clearly shows spatial and genetic links between the basement history, geomorphological evolution, and events of combustion metamorphism. The Late Paleozoic activity was associated with indentation of the Salair block into the Kuznetsk basin and attendant folding of coaliferous sediments into narrow, often overturned, folds (e.g., Zonenshain *et al.*, 1990). The folds were cut by a system of normal faults with their planes striking along the fold axes (Fig. 2). The edge normal faults were rejuvenated by Cenozoic orogenic events which produced long N-S striking steps intermediate in height between the Salair mountains and the Kuznetsk basin plainland. Deformation drew the sedimentary layers containing the thickest coal beds up to the day surface within the lowermost step, which now corresponds to the Prokopievsk-Kiselevsk coal mining area. The lowermost step is flanked by a step from the side of the Salair ridge (locally called Tyrgan) and a piedmont step on transition to the Kuznetsk basin. The Tyrgan step rises above the lowermost step and is about 80 m higher than the step adjoining the Kuznetsk basin. The latter is separated from Tyrgan by a clear-cut scarp of the Tyrgan reverse fault that experienced neotectonic rejuvenation. Rocks in the Tyrgan step are quite uniform in erosion strength and produce a terrain of a hilly plateau cut by transverse valleys, with elevations of 440 ~ 460m asl decreasing to 320 ~ 350m eastwards.

The step between Tyrgan and the Kuznetsk basin is separated from the latter by the Afonino-Kiselevsk reverse fault, which was likewise rejuvenated in the Cenozoic. Unlike the hilly Tyrgan step, this one has very unusual morphology due to strongly different physical properties (especially, erosion strength) of its rocks, which either burned or was spared by fire. The latter are easily eroded and the former are highly resistant. The surface topography consists of long parallel higher and lower ridges of high-temperature coal-fired rocks, truncated by rivers and brook valleys to make scenic cliffs. The ridges have steep southern and western slopes irrespective of the bedding of coal-bearing sediments.

The Salair complex reaches a width of 5 ~ 6km and totals a length of 45 ~ 50km. The orientation of ridges is fully controlled by the position of combusted coal beds. The area is drained in the W-E direction by the tributaries of the Aba river (Tom' catchment). The land between rivers looks like W-E striking low ridges crossed by chains of higher ridges composed of pyrometamorphic rocks that strike N-S along fold axes and faults. The "burned hills" rise 60 ~ 80m, or occasionally up to 120 m, above the surface (Krupennikov, 1935). At the beginning of coal mining in the Kuznetsk basin, some coal-fired ridges in the Prokopievsk-Kiselevsk area extended for three to five kilometers. Continuous sections of pyrometamorphic rocks still reach 1.5km

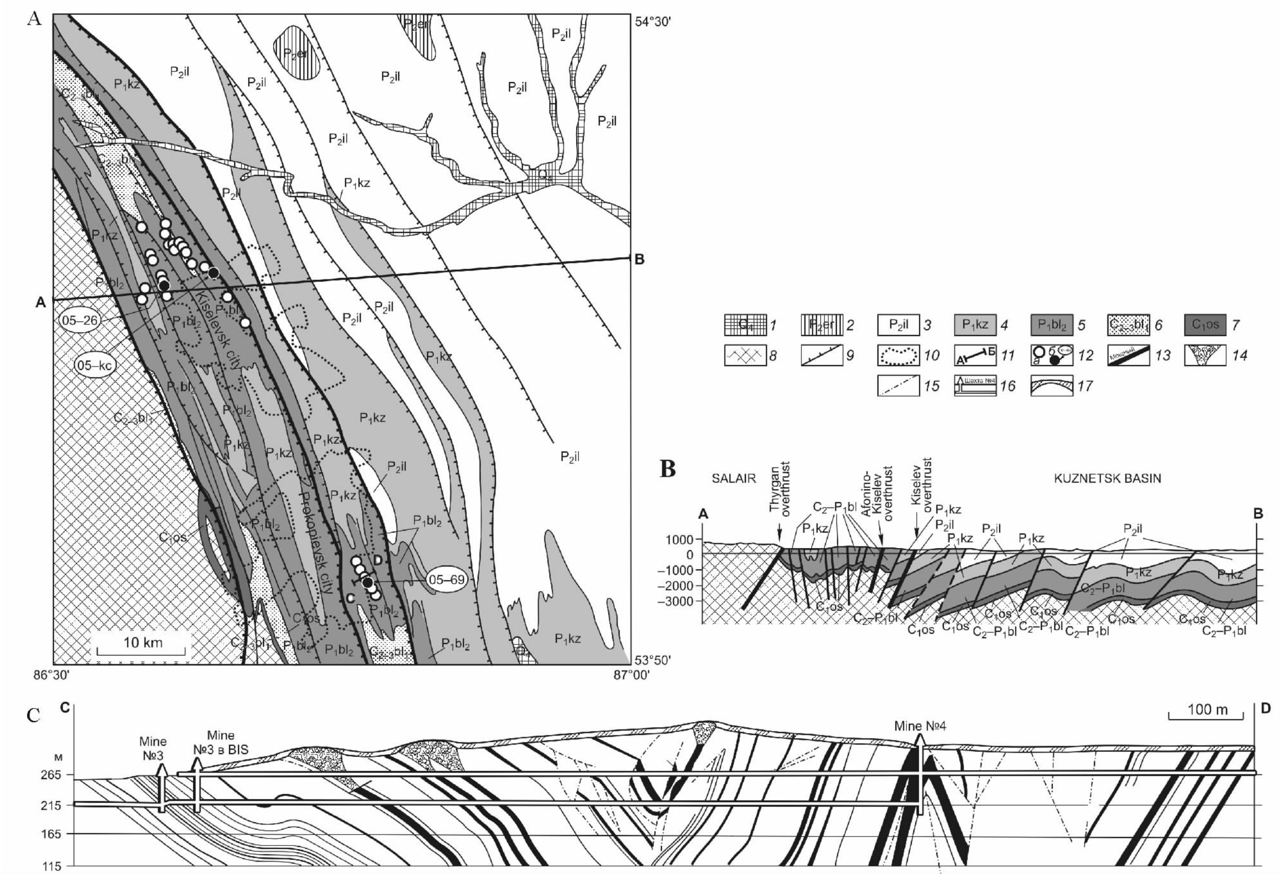

Fig. 2 A. Generalized geology of Prokopievsk-Kiselevsk area of Salair deformation zone, with sampling sites in pyrometamorphic complexes. B) Geological cross section along line A-B; C) Detailed cross section along line C-D (after Krupeninnikov, 1935). 1-fluvial deposits in river valleys, 2-Erunak subgroup, 3-Ilyinka subgroup, 4-Kuznetsk subgroup, 5-Upper Balakhon subgroup, 6-Lower Balakhon subgroup, 7-Ostrog Formation, 8-basement rocks of Kuznetsk basin, 9-main faults, 10-towns and villages, 11-geological profiles, 12-examined outcrops (a) and sampling sites for dating (b). Symbols in cross section C-D: 13-coal seams and their names, 14-pyrometamorphic complexes, 15-faults, 16-mines, 17-overburden

long, though a century of mining has changed dramatically the surface topography. The burned hills align with en echelon trenches and pitholes up to 40m wide and to 15m deep, a new man-caused landform that has been produced since the 1950s by rock collapses in place of the exhausted spots of unburned coal seams.

Natural coal fires in the Kuznetsk basin arise quite frequently at present but they are incomparably smaller than the great fires of old times. The deeply eroded hills of pyrometamorphic rocks must be quite old as denudation in the area is very slow. Large combustion metamorphic complexes are buried under loessy loam and are thus at least pre-Late Quaternary. An important fact, noted already by P. I. Butov and V. I. Yavorsky, is that coal fires never descended deeper than 3.5 ~ 5m above the level of modern river incision. Inasmuch, as the fire depth is limited by the depth of the groundwater surface (Eihwald, 1864; Cosca *et al.*, 1989), the Salair complex must have formed in the time when the erosion base was a few meters above the today's level. More evidence for quite an old age of those fires comes from the thickness and character of slope wash over the burned rocks. Valleys between the hills are commonly filled with up to 6 m thick torrential outwash containing pieces of weakly quenched metapelites and fine material of their supergene alteration. Deposits of this kind are easy to spot due to their reddish or pink color typical of surface burned rocks that arise under free oxygen supply. It is reasonable to assume that large fires were related to the early stage of neotectonic activity in the western basin periphery. We estimate, proceeding from geological evidence (tentative timing of the change from brown to gray Cenozoic molasse) that the oldest fires in the northern Altai-Sayan region may have occurred between 0.8 and 3Ma.

4 Pyrometamorphic complexes of the Salair zone

Combustion metamorphic rocks are abundant in the Kuznetsk basin and, with their typical habit, were recognized by the very first explorers. The old fires were the strongest and produced the largest pyrometamorphic complexes within the Salair belt of the deformed Balakhon coal-bearing sediments. The intensity of fires decays rapidly toward the basin center filled with Late Permian and Jurassic coal-bearing sediments where coal burned mostly in valley sides. Thus originated the exposures of coal-fired rocks in the right side of the Tom' river near Novokuznetsk, in the right side of the Inya river near Konovalovo village, and in the Chesnokovka valley. We examined 22 sites during the field trips of 2005-2006 in the center of the Kuznetsk basin and in its western and southern margins. The combustion metamorphic complexes are young, old, or of an intermediate age and differ in relations to the surface topography and in petrography. The man-caused and today's modern fires are beyond our consideration.

Young complexes are scattered in spots of tens to hundreds square meters varying in thickness from 3 to 20m. They occur most often in valley sides among shallow-dipping sedimentary layers, and their depths are limited by the first river terraces. They are easily detectable from their bright red color produced by impregnation with disseminated hematite. The latter fact indicates combustion in the zone of aeration. The combusted coal bed is sandwiched between sedimentary layers. Pyrometamorphic rocks are mainly weakly altered easily deformable varieties (yellow and pink clinkers). Collapse structures and the related fused rocks are local or absent. The overlying slope wash contains abundant clinker clasts but lacks pink argillic deposits that typically arise during strong physicochemical alteration. The section is capped by thin (to 0.3m) brown loam and modern soil. Young complexes have no geomorphic expression. They are especially typical of weakly deformed Upper Permian and Jurassic sediments in the basin center and are locally found in its southwestern margin.

Intermediate-age complexes build independent landforms (hills or hilly ridges) over thousands of square meters. Their upper layers (yellow and pink rocks) and the surrounding coal-bearing sediments are fully removed by erosion. Exposed rocks are mostly clinkers that preserve their protolith fabrics produced by medium-degree thermal alteration (Fig. 3 a, b, c, d). They are 5 to 15m thick, and erosion reaches a depth of 6 m. Below there are numerous fire sources with collapse breccias and melted rocks. The slope wash contains abundant clinker clasts. Pink clay spots in valleys between the combusted ridges are re-deposited chemically weathered clinkers. Pyrometamorphic rocks are often buried under up to 3 ~ 5 m thick brown loam and modern soil. Examples of these complexes are found in the Aba hills in Prokopievsk, and one such complex exists in the Kondoma meander near Malinovka village.

Old complexes make the most typical landforms in the area, consisting of 50 ~ 70m wide parallel ridges and hill chains stretching continuously for 0.5 ~ 1.5km. The rocks are exclusively high-temperature varieties with numerous collapse and explosion breccias (Fig. 3 e, f, j) and abundant products of full or partial melting of the protolith (Fig. 3 k, l, m, n, o, p). Pyrometamorphic rocks also exist as 3 ~ 6 m thick slope wash in valleys between hills. A great part of rocks is fully weathered into pinkish clayey material.

We made a special focus on high-temperature and deeply eroded pyrometamorphic rocks, which are most probable indicators of old fires induced by neotectonic activity. They are primarily thick layers within the block cut by cross faults that follow the Tugai and Kalzygai river valleys, where several parallel faults run along the general strike of the rocks. Two faults (Tyrgan and Afonino-Kiselevsk reverse faults) border the block in the west and east and are surrounded by younger roughly orthogonal small pinnate faults. Surface geological surveys and GPS measurements showed that most of large fires (both old and recent) occur within N-S faults. This is, for instance, a block between the Falcon hills in the east and Oktyabrinka village in the west enclosing four largest and longest ridges of high-temperature rocks. The fire temperatures may have exceeded 1000℃ (as is inferred from petrology), which could produce tightly coke and fused clinkers and breccias resistant to erosion. The thermally altered rocks have a tectonic contact with unaltered sediments on the western slope of one 1.2km long ridge along marked by argillic and carbonaceous shales. Deep open fractures separate clinkers from sediments and are occasionally found inside the ridges. The fault contact has an easily traceable trend following an area of hot gas venting associated with a modern fire.

Combusted coal beds are scattered within the study area though the pyrometamorphic rocks follow a consistent general strike. Coal may have burned continuously over distances of 1 ~ 3km or in spots of under a few hundreds of square meters. It often happened that only one of two coal beds burned. Burning of large volumes of coal (cores of anticlines or thick layers) commonly gave rise to pockets produced by roof collapse immediately during the fire or by explosion of the gas-coal mixture. Therefore the area abounds in breccias composed of clinker pieces baked together or cemented with paralavas. The roof collapse pockets often remained half-full with rock and groundwater filled the free space. This water, together with clinker clasts, broke through into coal - face during mining (Yavorsky and Radugina, 1932).

Fires always expanded from top to bottom of coal seams according to oxygen supply to the combustion area. We often saw high-temperature melted rocks over unaltered coal-bearing sediments at base of hills. Thus, the typical relationship of pyrometamorphic rocks with their protolith reported for many coal fires worldwide holds in the Kuznetsk basin (Butov and Yavorsky, 1922; Sokol *et al.*, 2005).

The combustion metamorphic complexes in the Salair zone of the Kuznetsk basin display a typical structure with distinct vertical zonation. Moderately altered clinkers top the modern section and overlie the ultrahigh-temperature rocks originated in deep sources. The sources are always composed of collapse or explosion breccias of different morphologies and lithologies. Almost all detritus in breccias is clinker after sandstones and mudstones (or siltstones) and varies in size from 5 ~ 10 to 50 ~ 70cm. The clinkers are glassy, porcelaneous, occasionally with traces of flow which indicates high melting degrees under more than 1000℃ (Bentor *et al.*, 1981; Sokol *et al.*, 2005). Fused rocks – iron-rich paralavas cementing clinker clasts – arise locally in sections that originally contained siderite. Cordierite paralavas with well pronounced shadow textures that record assimilation of metapelite formed in areas of ultahigh temperatures. In some cases rocks in combustion breccias are cemented by slags produced by partial melting of sandstones with carbonate cement. However, the most frequently found are pieces of clinkers welded together into a monolith. We saw only two outcrops that exposed the lower contacts of pyrometamorphic

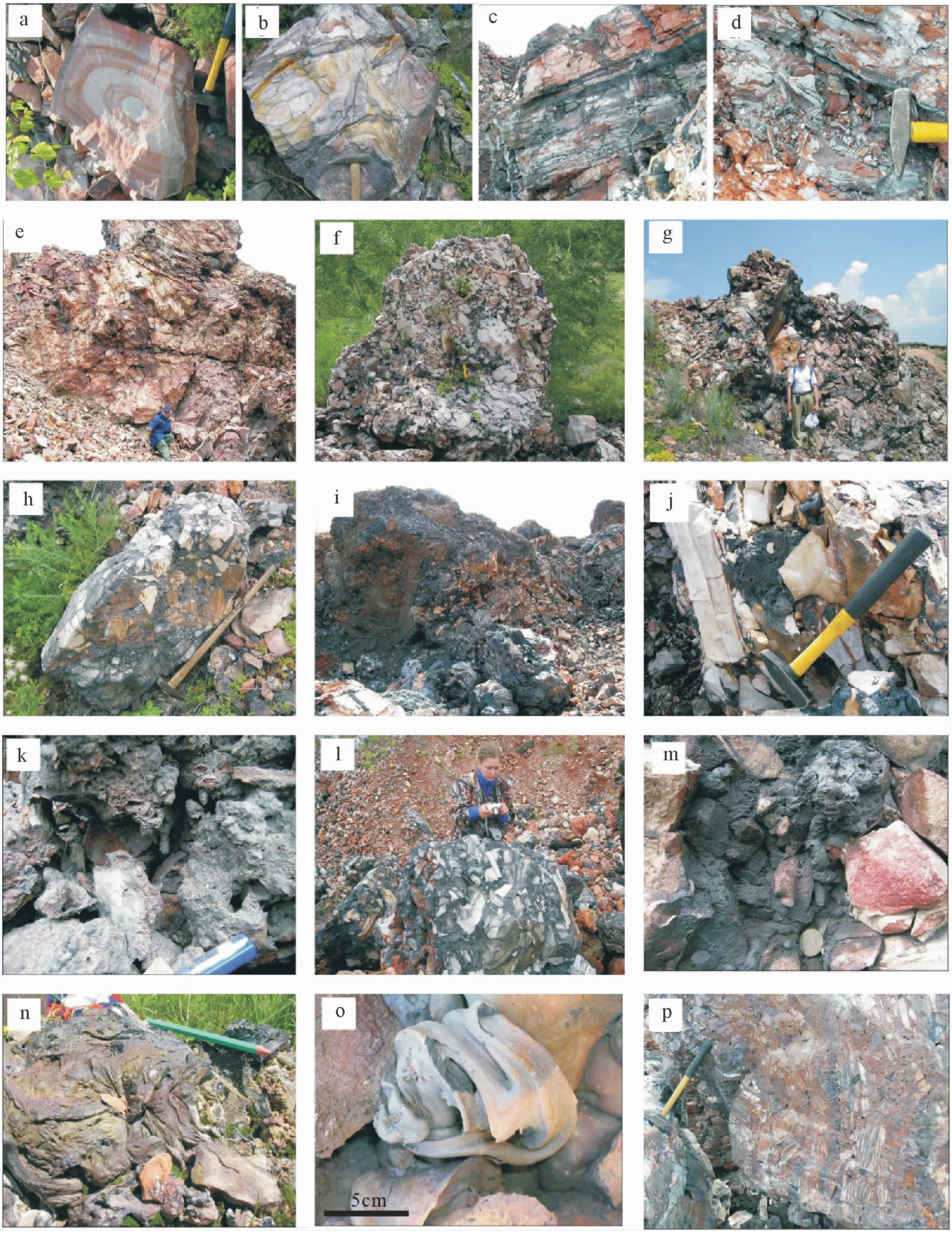

Fig. 3 Habit of clinkers (a-d), paralavas (e-j), pyrometamorphic breccias (k-p) from Kuznetsk basin. a-high-temperature clinker

produced by partial melting and vitrification of sandstone; concentric pattern imitating Liesegang rings produced by uneven distribution of finely disseminated hematite pigment (Aba hills, Prokopievsk); b-pieces of glassy clinkers welded into a monolith as indicator of ultrahigh temperatures and long time of fire; rocks of this kind are typical of deep underground sources (vicinity of Oktyabrinka village); c & d-coal-fire clinkers near Malinovka village; e-paralava cementing pyrometamorphic breccias; f-massive dark-gray cordierite paralava cementing clinker pieces assimilated to different degrees; g-black ferruginous paralava produced by fusion of siderite nodules contaminated with pelite; see well pronounced corrugated surface of solidified melt; h-corrugated surface of paralavas as indicator of sudden quenching of low-viscosity melt; i-queer shapes of paralava produced by melt squeezed out into inter-clinker space; j-massive cordierite paralava cementing clinker pieces assimilated to different degrees; k-bedrock exposure of explosion breccias; the constituent large clasts of clinkers are fused and baked into a monolith; l-fine-detrital collapse breccias consisting of porcelaneous clinkers cemented with thin paralavas streaks; m-large clinker blocks cemented with massive and streaky paralavas; n-high-temperature collapse breccias dominated by fused material of paralavas as cement; clinker pieces in them are assimilated by paralava to different degrees, up to the appearance of shadow structures; o, p-collapse breccias from pyrometamorphic complex of an intermediate age; clinker clasts are cemented with paralava and slag.

rocks with coal-bearing sediments where the former immediately overlie unburned coal beds. The latter bear signature of high-temperature effects only in their upper 30 ~ 60cm (looking denser and more glossy), and no visible traces of fire are found below.

5 Discussions and Conclusions

5.1 Old fires: scales and causes

The Salair pyrometamorphic complex is remarkable by its great size (45km long and 5 ~ 6km wide) and high formation temperatures. The temperatures of underground fires that acted upon terrigenous rocks exceeded 900 ~ 1000℃, as can be inferred from abundant tridymite, cristobalite, potassic cordierite, and mullite minerals in clinkers and paralavas coexisting with large volumes of felsic K-Al glasses. The Salair complex has exceptionally long and continuous burn zones unlike its counterparts in which these zones are scattered. The Salair burn zones exist today as kilometers long strips of rocks fully transformed by melting and then quenching into material similar in composition and properties to glassy cordierite ceramics. That is why the rocks are so much resistant to erosion and form the modern topographic highs.

Yavorsky and Radugina (1932) reported that traces of coal fires were found everywhere in the basin, but especially large fires acted in the southwest, in the Salair belt, between Zenkovaya village and Krivoi Uskat mountain. Had the intensity of fires depended uniquely on quality and caloricity of coal, clinkers and paralavas rocks would have occurred throughout the western periphery of the Kuznetsk basin. Therefore, the scale of old combustion events was controlled jointly by several factors. The Prokopievsk-Kiselevsk coal area (Karasevich *et al.*, 2001) has the greatest thickness (820m on average) of the Upper Balakhon subgroup with up to 10.2% coal (nearly the highest limit). The coal, in turn, has very high gas contents, even more than generally in the Kuznetsk basin which is a great methane province. Coal is mainly anthracitic or moderately altered varieties that occur in high-caloricity half-matte gas-producing beds with up to 55% vitrinite. The producing beds total a thickness of 60 ~ 80m and individual beds reach 14m thick (Moschny, Gorely and Vnutrenniy IV). They are strongly fractured and have high methane contents of 10 ~ 15 cubic meters per ton coal at zero horizon, 14 ~ 19m^3/ton at horizon-100, and 19 ~ 24m^3/ton at horizon-300. All mines in the area have high gas blow-out risk and gas contamination beyond all standards. Many coal seams are specific gas traps and have high gas contents in close and semi-close anticlines (e.g., in the Taiba anticline) of the Balakhon rocks. Large faults play an important part in upward gas migration and accumulation. They can either increase (screening faults) or decrease (draining faults) gas contents of coal beds, the number of cases being roughly equal. The screening faults are thrusts or most often conformal longitudinal reverse faults with their planes dipping at 50 ~ 60°. They were also key agents in secular degassing of coal seams.

According to mining documents, the pockets of crushed burned rocks become two or three times thicker near the surface than their source coal beds (Krupeninnikov, 1935). The cone-shaped geometry of brecciated layers of burned rocks at the surface on the extension of coal beds cannot have been produced by roof collapse only, but rather results from shallow gas explosions in which rocks collapsed into the explosion funnel.

The old coal fires were exceptionally great in the Prokopievsk-Kiselevsk belt where they were triggered by detonating gas blow which ignited the methane-coal mixture. Death-risk gas blow-out remains today an urgent problem of coal mining in the Kuznetsk basin, and especially in the Prokopievsk-Kiselevsk area. The presence of free gas prior to gasification of solid fuel is the key point that allows fire sweeping from the firing point along the surface of a coal seam. Spontaneous gas blows may have produced the numerous explosion breccias and the related ultrahigh-temperature metamorphism expressed as melting and vitrification of clinkers and the ensuing consolidation of their fragments into monoliths.

5.2 Time of combustion metamorphism events

Four fifths of rock volume in sections of weakly eroded pyrometamorphic complexes are normally weakly or moderately altered high-temperature metamorphics while fused rocks are restricted to the root (source) zones. This proportion holds in different pyrometamorphic sections worldwide (Sokol *et al.*, 2005). The 20 ~ 50m thick root parts of the section we studied are exposed on the surface along the Tyrgan reverse fault. Therefore, erosion removed the 80 to 200 m thick overburden of weakly altered rocks for the time elapsed since the origin of the complex. This process can take a few millions of years in the conditions of low mountains in a wet climate. More evidence for the old age of these formations comes from geology, namely the presence of 3 ~ 6m thick layers of redeposited weathered clinkers overlain by brown loessy loam and mature soils in valleys between clinker ridges.

The events of combustion metamorphism in the Salair zone of the Kuznetsk basin were timed using data on the above six paralava samples (Fig. 4; Table 1).

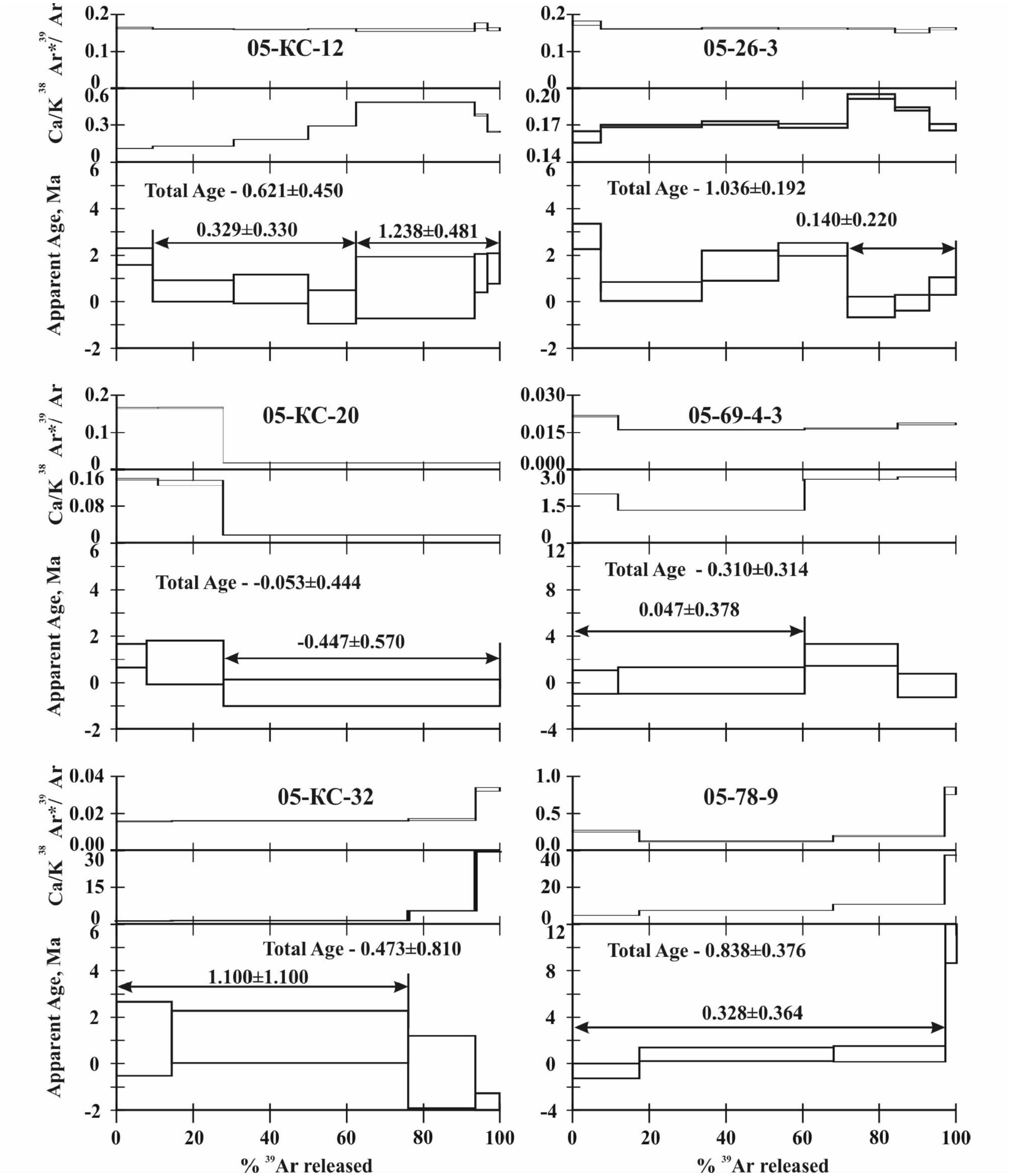

Fig. 4 $^{40}Ar/^{39}Ar$ ages of pyrometamorphic rocks from the Salair combustion metamorphic complex

Table 1 Results of $^{40}Ar/^{39}Ar$ dating of paralavas from old coal fires of the Kuznetsk basin (J-value based on an Age of 128.1Ma for LP-6 biotite and an Age of 18.5Ma for Bern-4m muscovite)

№	T (℃)	t (min)	^{40}Ar (10^{-9} stp)	$^{40}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Ca/K	$\Sigma^{39}Ar$ (%)	Apparent Age (Ma ±1σ)
					Sample 05-КС-12. $J=0.004575\pm0.0000546$					
1	500	10	17.83	3.30	0.018	0.03	0.010	0.11	9.4	1.9 ±0.4
2	650	10	33.91	2.80	0.018	0.04	0.009	0.13	30.6	0.5 ±0.5
3	750	10	30.29	2.72	0.018	0.05	0.009	0.18	50.0	0.5 ±0.6
4	850	10	27.49	3.84	0.018	0.08	0.013	0.29	62.5	−0.2 ±0.7
5	950	10	149.52	8.44	0.021	0.13	0.028	0.48	93.4	0.6 ±1.3
6	1050	10	25.66	13.24	0.025	0.11	0.044	0.38	96.8	1.2 ±0.8
7	1150	10	23.08	12.45	0.024	0.07	0.042	0.25	100.0	1.4 ±0.7
					Sample 05-КС-20. $J=0.004517\pm0.000053$					
1	600	10	13.26	1.82	0.018	0.04	0.006	0.14	10.8	1.2 ±0.5
2	900	10	36.64	3.23	0.019	0.04	0.011	0.13	27.7	0.9 ±0.9
3	1200	10	41.16	0.85	0.002	0.00	0.003	0.02	100.0	−0.4 ±0.6
					Sample 05-КС-32-2. $J=0.004487\pm0.000052$					
1	550	10	10.37	3.69	0.018	0.32	0.012	1.14	14.3	1.0 ±1.6
2	700	10	19.17	1.58	0.017	0.36	0.005	1.29	76.1	1.1 ±1.1
3	850	10	5.15	1.50	0.018	1.48	0.005	5.32	93.6	−0.4 ±1.6
4	1150	10	4.96	3.95	0.036	8.11	0.015	29.19	100.0	−4.8 ±3.5
					Sample 05-26-3. $J=0.004505\pm0.000053$					
1	500	10	10.90	3.50	0.020	0.04	0.011	0.16	7.3	2.8 ±0.5
2	650	10	38.50	3.43	0.018	0.05	0.011	0.17	33.7	0.4 ±0.4
3	750	10	42.47	5.01	0.019	0.05	0.016	0.17	53.7	1.5 ±0.6
4	850	10	58.40	7.62	0.021	0.05	0.025	0.17	71.7	2.2 ±0.3
5	950	10	44.88	8.52	0.022	0.05	0.029	0.19	84.1	−0.2 ±0.4
6	1050	10	31.31	8.20	0.021	0.05	0.028	0.18	93.0	−0.1 ±0.3
7	1150	10	29.42	9.91	0.022	0.05	0.033	0.17	100.0	0.7 ±0.4
					Sample 05-69-4-3. $J=0.004421\pm0.000051$					
1	600	10	7.69	1.78	0.023	0.55	0.006	1.99	11.9	0.0 ±0.5
2	800	10	8.47	0.48	0.016	0.37	0.002	1.33	60.5	0.1 ±0.6
3	1000	10	7.21	0.82	0.017	0.72	0.002	2.59	84.8	1.2 ±0.5
4	1200	10	7.63	1.38	0.019	0.74	0.005	2.68	100.0	−0.1 ±0.5
					Sample 05-78-9. $J=0.004384\pm0.00005$					
1	600	10	10.66	1.84	0.017	1.29	0.007	4.66	17.3	−0.7 ±0.6
2	800	10	25.43	1.50	0.017	2.02	0.005	7.28	68.0	0.8 ±0.6
3	1000	10	16.63	1.71	0.018	2.91	0.005	10.47	97.0	0.8 ±0.7
4	1200	10	5.61	5.63	0.021	10.32	0.015	37.14	100.0	10.3 ±1.7

Sample 05-KC-12. The Ca/K ratios in the sample range from 0.1 to 0.5 which indicates its phase heterogeneity. The uneven Ca/K ratios and their relatively high values at high-temperature steps prompted us to distinguish two intermediate plateaus consisting of three successive steps. The plateau in the middle part of the spectrum, containing 53% of the total ^{39}Ar released from the sample, corresponds to a higher-K gas fraction and gives an age of 0.329 ± 0.330Ma, whereas the plateau of the high-temperature step, with high Ca/K ratios and 37% released ^{39}Ar, indicates a relatively old age of 1.238 ± 0.481Ma. It is unlikely that the sample would carry excess radiogenic argon, because its protolith melted completely in an open flow system at intense outgassing and it lacks relic primary minerals. The results we obtained apparently indicate an age heterogeneity of the sample. Its younger age may have been caused by later reheating of the 1.238 ± 0.481Ma rock, which affected a phase with a less stable isotope system. Taking into account the Ca/K variations, we infer that the greatest part of total ^{39}Ar released in the high-temperature step from the Ca-rich glassy matrix likely having a more retentive isotope system resistant against later thermal disturbance.

Sample 05-26-3 shows ages from 2.8Ma to −0.062Ma, with relatively high values in two steps in the middle of the spectrum. The high-temperature step gives a plateau containing 28% released ^{39}Ar, an age of 0.140 ± 0.220Ma and high Ca/K ratios. The integrated total-gas age, equivalent of the K/Ar age, is as old as 1.036 ± 0.192Ma. The difference can be due to the age heterogeneity, as in 05-KC-12, but the older component does not show up as an intermediate plateau.

Sample 05-KC-20. The final (third) step contains the greatest percent of released ^{39}Ar (72%) and shows an age of 0.447 ± 0.570Ma. This date is consistent with the total-gas age of 0.053 ± 0.444Ma. Thus, the sample formed no earlier than 0.123Ma ago, at a 95% confidence level.

Sample 05-69-4-3. Old ages and high Ca/K ratios correspond only to the third step. For two first steps containing over 60% released ^{39}Ar, we infer an age of 0.047 ± 0.378Ma. The total-gas age of 0.310 ± 0.314Ma agrees with the age of the intermediate plateau. Therefore, the sample is no older than 0.425Ma.

Sample 05-KC-32-2 has very low radiogenic argon which causes large age errors. 76% ^{39}Ar released in two steps with consistent values, and their average gives 1.086 1.100Ma. The total-gas age is younger (0.473 ± 0.810Ma) due to the contribution from two high-temperature steps, though it agrees with the plateau age within the uncertainty.

Sample 05-78-9. The age spectrum of the sample contains a plateau satisfying the criteria from Fleck *et al.* (1977). 97% ^{39}Ar released in three successive steps with consistent ages and Ca/K ratios. Thus, the age of the sample is to a great probability 0.328 ± 0.364Ma.

The obtained plateau ages (from the intermediate plateau determined using the criteria from Fleck *et al.* (1977)) and the total-gas ages are shown in Fig.5. The age of sample 05-78-9 is a plateau age. Samples 05-KC-20, 05-KC-32, and 05-69-4 have their plateau ages consistent with the total-gas ages, thus the age of the intermediate plateau corresponds to the time when the rock formed. Samples 05-KC-12 and 05-26-3 appear to have discordant ages including an old component about 1Ma and the youngest components.

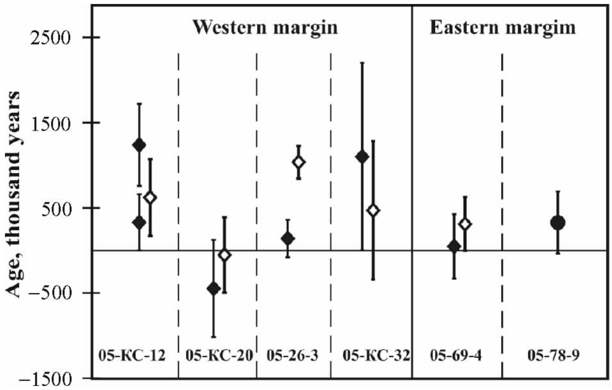

Fig. 5 Synthetic $^{40}Ar/^{39}Ar$ data for pyrometamorphic rocks from the western and eastern margins of the Prokopievsk-Kiselevsk block. Bold rhomb is intermediate plateau age; open rhomb is total-gas age; black circle is plateau age estimated according to the criteria by Fleck *et al.* (1977).

Thus, (i) the samples from the eastern margin of the Prokopievsk-Kiselevsk block show a young age of 0.193 ± 0.262Ma (weighted mean plateau ages for samples 05-69-4 and 05-78-9) and (ii) the samples from the western margin show at least two age components: 1.216 ± 0.441Ma (weighted mean old plateau age for sample 05-KC-12 and the plateau age of 05-KC-32) and 221 ± 174 Kyr (weighted mean young plateau age for sample 05-KC-12 and the plateau ages of 05-KC-20 and 05-26-3).

Note that numerous and time spaced firing events in neighbor areas is a common phenomenon in caustobiolith provinces (Heffern and Coates, 2004; Sokol *et al.*, 2005). These events were investigated in detail using $^{40}Ar/^{39}Ar$ dating of rocks from the pyrometamorphic complex of the Hatrurim basin in Israel (Gur *et al.*, 1995).

Other paralava samples we studied allowed us to time the events of combustion metamorphism and the causative tectonic events on the eastern margin of the Prokopievsk-Kiselevsk block (sample 05-69-4-3, Aba hills, Prokopievsk) and south of the block (sample 05-78-9, Malinovka village). The rocks formed no earlier than 0.425 ~ 0.690Ma ago. Hence, the Afonino-Kiselevsk reverse fault, which is the block eastern boundary reactivated about 0.425Ma ago and since then it has delineated the piedmont step of the eastern Salair margin. The medium degree of alteration in the complex agrees well with the inference of its intermediate age.

5.3 Neotectonic control of pyrometamorphic complexes

Broad occurrence of high-temperature pyrometamorphic rocks (paralava and glassy clinker) indicates that coal-bearing sediments on the western periphery of the Kuznetsk basin were swiftly drawn to the surface simultaneously over the entire border between the Prokopievsk-Kiselevsk block and Salair, which can have been possible only due to neotectonic movements. The space distribution of dates proves valid the scenario suggested for the evolution of transition zones from neotectonic orogens to basins reconstructed from geological evidence. This scenario fits the universal law of mountain growth propagation in which basin peripheries, cut off along reverse faults, become progressively involved into uplift. The oldest ages within the interval of combustion metamorphism (1.216 ± 0.441 Ma) correspond to the onset of uplift that produced the rugged terrain of the Kuznetsk basin western margin, when the Salair block began to thrust over the Kuznetsk basin. Today combustion metamorphic complexes of that age occur outside the Kuznetsk plain, within Tyrgan (which is now the lower step of the Salair upland). The Tyrgan step strikes in the N-S direction and is bounded in the west and east by Late Paleozoic-Early Mesozoic faults reactivated in the Late Neogene-Quaternary, as indicated by reverse scarps dipping westward beneath the Salair. The place was exactly the Kuznetsk basin-Salair junction at the inception time of the latest tectonic event. The Tyrgan area experienced the highest recent uplift which was responsible for methane outgassing from coal beds and the ensuing coal fires. The younger ages of 0.193 ± 0.262 Ma represent combustion metamorphic complexes located east of the Tyrgan step, including those at the modern boundary of the Kuznetsk plain. Their relatively young ages are confirmed by their weaker erosion.

Thus, the first dates obtained using the new approach show that the main stage of neotectonic activity at the northern edge of the mountain province of southern Siberia began at the Neogene-Quaternary boundary, and a later stage of accelerated movements followed in the Middle Pleistocene. The available ages of rocks record a trend of deformation expansion from the Salair upland toward the center of the Kuznetsk basin.

5.4 $^{40}Ar/^{39}Ar$ dating as applied to pyrometamorphic rocks: Special remarks

The samples of combustion metamorphic rocks fit for $^{40}Ar/^{39}Ar$ dating should contain fully transformed protolith minerals, high bulk contents of K and low or medium C, and include potassium concentrating phases in newly formed melted rocks, especially large amounts of potassic glasses.

Samples of paralava produced by old fires were dated by the $^{40}Ar/^{39}Ar$ incremental heating technique. The isotope ratios were corrected for Ca-, Cl-, and K-derived Ar isotopic interferences, identified using mineralogical criteria. The interpretation of age-spectrum results was checked against internal (plateau and isochrone ages) and external ("couple criterion" after Morozova *et al.*, 1987) criteria, and against conventional relative ages inferred from geological and stratigraphic evidence. The habit of crystalline phases in clinker and paralava (dendritic, skeletal, or cased crystals) and abundant fresh glass suggest quench cooling of combustion melts. Hence, the diffusion exchange ceased and the K/Ar system closed suddenly (in geological time scale) during the cooling. It means that the $^{40}Ar/^{39}Ar$ dates record exactly the time when combustion stops at a specific point.

So far dating has been restricted to paralava, which is a limitation of the method because paralava is much scarcer than clinker and often has unfit chemistry. To help the problem, we further expect to adapt the $^{40}Ar/^{39}Ar$ procedure to clinker, the common rock at any coal-fire site. This improvement will make the method a reliable tool for timing neotectonic events along the edges of mountain terrains that border coal basins.

The development of the new approach implying investigation and $^{40}Ar/^{39}Ar$ dating of combustion metamorphic complexes in Central Asia, especially in the Gorny Altai and in the Kenderlyk and Junggar basins, will create grounds for a chronologically consistent model of the latest orogeny in southern West Siberia.

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