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Paleozoic crustal growth and metallogeny of Central Asia: evidence from magmatic-hydrothermal ore systems of Central Kazakhstan ☆

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Abstract

The ore deposit spectrum of Central Kazakhstan reflects a range of lithospheric magmatism controlled by the polycyclic geodynamic evolution of an active continental margin which develops from back-arc oceanic settings (volcanic-hosted massive sulphide Cu–Au ore deposits) to subduction-controlled calcalkaline magmatism (copper porphyries) with subsequent stages of crust differentiation of low-degree partial melting and extended intramagmatic fractionation (molybdenum porphyries) on to continental rifting (peralkaline REE–Zr–Nb-rich systems). Mesothermal gold deposits mark transcrustal shear-zone controlled fluid conduits formed during arc slicing and thermal relaxation in a post-orogenic setting. The ore deposits characterize successive and spatially overlapping stages of crustal growth and consolidation.

The general subduction setting of this range of ore deposits is reflected by calc-alkaline trends in the associated subalkaline, high-K felsic rocks with a wide range in silica contents. The predominant metal spectrum of Au, Cu and Mo indicates relatively oxidized magmatic-hydrothermal systems, in accordance with the metaluminous I-type nature of their igneous host rocks, i.e. oxidized igneous precursor material.

Despite of presumably highly variable ratios of mantle/crust components in individual magmatic systems (gabbros to leucogranites), most rocks have very similar positive initial εNd values of 0 to +5.5, and depleted mantle model ages in the range of 500–800 Ma. The ubiquitous relatively young mantle extraction age is likely to characterize the lower crust of Central Kazakhstan. This basement is interpreted as back-arc oceanic crust that formed behind oceanwards drifting continental-margin slivers during the initial stages of the active continental margin evolution of the Late Precambrian Angara–Baltica supercontinent. The early back-arc oceanic crust was transformed into the present lower crust during the Paleozoic orogenic evolution, in which the back-arc crust was buried by magmatic arc and sedimentary material and recurrently affected by high-grade metamorphism, basaltic melt injection/underplating, and granitic melt extraction. Anorogenic rift-related Permian peralkaline riebeckite granites with REE–Zr–Nb mineralization have very high positive εNd of +5 to +8, which is probably inherited from young subcrustal lithosphere at the mantle/crust boundary that was affected by partial remelting due to asthenospheric upwelling during rifting. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Paleozoic crustal growth; metallogeny; magmatic-hydrothermal ore systems

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1. Introduction

Ore deposits form the exotic end members of the general rock spectrum and define very advanced stages of petrochemical fractionation processes. These processes develop on a specific geodynamic background, which allows ore deposits to be used as distinct markers for the geodynamic evolution of a given region (Mitchell and Garson, 1981; Sawkins, 1990).

Central Asia is characterized by a wide spectrum of ore deposits, and its general geodynamic evolution is discussed in two opposing models. The modern reconstruction of the Central Asian mobile belt as a single elongated island-arc system by Sengör et al. (1993) and Sengör and Natal'in (1996), with magmatic fronts as markers for convergent plate boundaries, puts the Paleozoic fold belts of Central Asia into a geodynamic context of accretionary orogeny. This model attributes continental growth to the addition of accretionary prism material along episodic oceanward subduction-zone jump-backs, and the subsequent amalgamation to and with continental crust by arc magmatism, implying a gradual younging of the crust from older to younger foldbelts.

The relatively well-known surface geology of Central Kazakhstan allows a general paleotectonic reconstruction of the Paleozoic evolution, but leaves much room for speculation. Given the lack of isotope and trace-element key data on the igneous rocks, there is no information on the deeper parts of Kazakhstan and, accordingly, a range of scenarios is still under discussion.

Most local geologists believe in an ancient continental precursor of Central Kazakhstan ("Kazakhstan micro-continent") that during various "tectonomagmatic reactivation" events is thought to have been affected by rifting and subsidence, giving room for the deposition of sediments and volcanics, and the emplacement of plutonic rocks (see compilation in Glukhan and Serykh, 1996). In this largely fixistic geosynclinal viewpoint, the dispersed Precambrian massifs are uplifted blocks of an old crystalline basement underlying the whole area. Popov (1996), in a recent reemphasis of the static geosynclinal viewpoint, assumes a large asthenospheric diapir beneath the inferred old continental crust of Central Kazakhstan. This diapir is believed to have been stationary throughout the Paleozoic, causing repeated rifting and subsidence of the old crust, and the formation of island arcs. Such a large crystalline basement should have left its isotopic signature in those Paleozoic magmatic rocks, which have interacted with the lower crust, e.g. the large-scale granitic rocks. The granitic magmatism can therefore be used as a probe into the deeper crust of Central Kazakhstan and should allow discrimination of the two opposing geotectonic models.

Other plate-tectonic concepts for Central Kazakhstan transcribe the geosynclinal terms, and assign the orogenic cycles to a number of complete Wilson cycles, with the frequent opening and closure of small oceans and subsequent collisions of microcontinents (Zonenshain et al., 1990). It was also proposed that the Central Asian mobile belt consists of a collage of independent terranes (Coleman, 1989). These theories would suggest a rather heterogeneous isotopic pattern for the wide-spread Paleozoic felsic magmatism.

Although a few thousand K–Ar age-determinations define the temporal distribution of magmatic events for Kazakhstan (Kostitsyn, 1996), Rb–Sr isotope data are sparse and Sm–Nd isotope data are non-existent; thus the age and character of the buried basement remains unknown. Our study focuses on the geochemistry and isotope geochemistry of igneous rocks associated with ore systems. These ore systems can be regarded as diagnostic of geotectonic setting, when compared with more recent equivalents, such as ore deposits of the circum-Pacific volcanoplutonic belts. The sampling strategy was to collect the broadest possible range of least altered plutonic rocks from ore deposits throughout Central Kazakhstan and adjoining areas. The set of samples has reconnaissance character and aims at definition of large-scale geodynamic/petrologic processes.

2. Geological setting

The Paleozoic Central Asian orogenic belt reaches from the southern tip of the Urals over Kazakhstan, North-West China and Mongolia to the Ochotsk Sea in the Russian Far East. Suess (1901) had already recognized that this region had peripherally arranged foldbelts mainly to the west and south of the Angaran nucleus (also known as Siberian Platform) with successively younger ages away from the craton. A common characteristic feature of the individual orogens of the Central Asian orogenic belt is the complex but recurrent arrangement of dominantly accretionary-prism and magmatic-arc material, interspersed with massifs of older continental crust and slivers of oceanic crust (Sengör et al., 1993). Central Kazakhstan displays a large oroclinal bend of Paleozoic foldbelts, which grow from Cambrian to Ordovician age in the outer part to Carboniferous ages in the central part (Fig. 1).

Outcrops of Precambrian continental crust are confined to the older Ordovician to Silurian fold systems framing Central Kazakhstan to the north and to the west (Fig. 1). The gneisses and quartzo-feldspatic schist units of these ancient sequences closely resemble those of the margins of the Baltic shield and Eastern European platform. Most prominent is the Kokshetav massif to the north of Central Kazakhstan, which has an Archean crystalline basement of granulite- and amphibolite-facies rocks with fragments of Vendian/Cambrian ultra-high pressure garnet-mica schists (Kasymov, 1995; Zhang et al., 1997).

There are a number of irregularly distributed remnants of Lower Paleozoic oceanic crust in Central Kazakhstan. However, in contrast to examples from collisional orogens, these ophiolite rocks do not mark interplate suture zones (Sengör et al., 1993) and show features of back-arc oceanic crust (Nikitin, 1995; Kröner, 1998). The ophiolite belts of Central Kazakhstan in general comprise only the top-most layers of paleo-oceanic crust, consisting of deep-sea sediments and volcanic rocks. These have ages up to Middle Ordovician, but rarely preserved deeper igneous layers may be as old as Vendian (Nikitin, 1995). The oceanic-crust formations host massive-sulphide Cu–Au deposits.

The first oceanic island-arc system of Kazakhstan developed during Cambrian to Early Ordovician times from predominantly mafic volcanism (Spiridonov, 1996). Horizontal stacking by strike-slip action obscured the originally elongated island-arc and formed the so-called "Comb of Northern Kazakhstan" (Sengör et al., 1993). Magmatism continued during arc deformation, and the emplacement of the 440–450 Ma-old Zerenda and Krykkuduk calcalkaline batholiths consolidates the disrupted island-arc fragments (Shatagin, 1994; Spiridonov, 1996). The Late Ordovician orogeny largely established continental conditions for Central Kazakhstan, and the newly formed Devonian volcano-plutonic belt is a continental magmatic arc. Continental conditions also prevailed during formation of the superimposed Carboniferous arc. Arc magmatism ceased in early Permian times, when the platform stage was reached, that lasts until today.

Large granodioritic batholiths of Ordovician, Devonian and Carboniferous ages characterize the axes of the magmatic arcs and reach up to 500 km in strike length and several tens of km in width. The Devonian and Carboniferous large-volume granodioritic magmatism is followed by leucogranitic magmatism. The small-scale leucogranitic intrusions recurrently occur after a time gap of up to 20 Ma. In contrast to the linear batholith belts, leucocratic granites have isometric shapes controlled by extensional regimes in pull-apart structures and also occur far off the magmatic fronts in the hinterland.

2.1. Sampling and laboratory procedure

A sample suite of about 300 rock specimens was obtained from a number of ore deposits and rock outcrops of Central Kazakhstan and adjoining areas. Often, the remains of the extensive exploration activities of the past decades provided the opportunity to sample very fresh rock material. The sampling was guided by local geologists familiar with the field relationships of the igneous rock spectrum. A selection of 140 rock samples was studied by petrography and geochemistry, and 30 samples were selected for Sm–Nd isotope study. Rb–Sr isotopes were determined on 20 samples. The investigated localities include the mesothermal gold–quartz type mineralizations at Aksu, Stepnyak, Bestube and Zholymbet in the north of Central Kazakhstan, Dollinye east of Balchash and Akbakai to the south-west of Central Kazakhstan. The rock suites associated to Cu porphyries were sampled at Boshekul (North Kazakhstan), Samarskoye (north of Karaganda), Kounrad (near the town of Balchash), Sayak (eastern Lake Balchash) and Aqtogay to the south-east of Central Kazakhstan. Samples of Bozshekul and Samarskoye were found highly altered and thus not suitable for geochemistry and only few samples of Aqtogay and Kounrad were chosen for isotope geochemistry. Sites with very fresh material of leucogranites were found throughout the molybdenum province north of Lake Balchash at Nurataldy, Bainazar, Aqshatau, Bektauata and East Kounrad.

The standard preparation procedure was to crush specimens of 2–5 kg, and grind a split of about 100 g down to <200 μm in an agate mill. Major elements and a number of trace elements were analyzed by X-ray fluorescence spectrometry on glass pellets (Li-tetraborate flux). Loss on ignition was determined from the differential weight after heating to 800°C. A broad suite of trace elements was analyzed by ICP-MS, some additional elements were analyzed by neutron activation analysis. Table 1 lists only those geochemical samples on which isotope analysis was done.

Sm–Nd and Rb–Sr isotopic determinations were done by the isotope dilution method. Dissolution of the spiked rock powders (~100 mg) was done by $H_2SO_4 + HNO_3 + HF$ digestion in sealed teflon vessels for 24 h at 170°C, and recurrent drying at 140°C on hot plates and HCl treatment until complete anion replacement by Cl^-. Rb, Sr and REE separation was accomplished by passing the solutions through ion-exchange resin columns (AG50WX8, 200–400 mesh). Sm and Nd concentrates were obtained by subsequently passing the REE-fraction through columns with HDEHP-coated Teflon powder. The measurements were done at the Geology Department of the University of Göttingen, on a Finnigan MAT 262RPQ + thermal-ion mass-spectrometer using double Re-filaments for Sm and Nd and single Ta-filaments for Sr. Rb isotope determinations were done with double Ta-filaments on a Finnigan MAT 60 quadropol mass-spectrometer. Parallel analyses of the LaJolla Nd ($n = 42$) and NBS-987 Sr ($n = 51$) standards yielded values of 0.51185 ± 5 (2σ) and 0.710244 ± 11 (2σ), respectively.

3. Ore deposits and associated rock spectrum

3.1. Mesothermal gold deposits

Kazakhstan has a number of Ordovician to Carboniferous gold occurrences, which closely resemble the common Archean greenstone Au mineralization style in terms of native-gold dominated ore paragenesis, large vertical continuity and structural setting. The overall structural control of the mesothermal gold deposits is by postmetamorphic transcrustal shear zones, but gold mineralization occurs only in those transects where these structures cut accreted oceanic island-arc material on former back-arc oceanic crust (Spiridonov, 1996).

Mesothermal Au–quartz vein type mineralization is most pronounced in the north of Central Kazakhstan, where the main deposits have been in operation since the start of the century with individual cumulative production figures in excess of 200 t Au. The gold deposits and their regional geology have been studied in detail by Spiridonov, as summarized by Spiridonov (1996). Most often they are hosted by minor multiple intrusions. These smaller plutonic bodies occur along strike-slip shear zones at the borders of the large tonalitic to granodioritic and granitic Krykkuduk and Zerenda batholiths of the Stepnyak synclinorium and Kokshetav massif. The geologic record of the Stepnyak synclinorium starts with Vendian oceanic crust of back-arc geochemical character. Calcalkaline tholeiite, shoshonite and boninite volcanic rocks of Cambrian and Early Ordovician ages are intruded by gabbros and dolerites of the Arenigian Aksu complex. During the Middle to Late Ordovician an oceanic volcanic island arc with conjugated flysch troughs evolved. The fragmentation and subsequent amalgamation of the island-arc system with the continental fragment of the Kokchetav massif at the end of the Ordovician is accompanied by emplacement of a large volume of tonalitic to granitic rocks constituting the Krykkuduk and Zerenda batholiths. Shatagin (1994) determined a Rb–Sr isochron age of 448 ± 9 Ma for the Zerenda batholith, similar to K–Ar ages from the satellite intrusions at the Aksu, Zholymbet and Stepnyak ore deposits (Spiridonov, 1996).

The Zerenda batholith has two major magmatic phases, of which the later granodioritic to granitic unit was considered to be of lower crustal origin (Shatagin, 1994). However, it has initial $^{87}Sr/^{86}Sr$ ratios of 0.7046 (granodiorite) to 0.7059 (granite).

Fig. 1. Major ore deposits and magmatic arcs of Central Kazakhstan, and sample location for Nd isotope data. The Central Kazakhstan oroclinal bend is reflected by the inward younging of major magmatic arcs towards Lake Balkash.

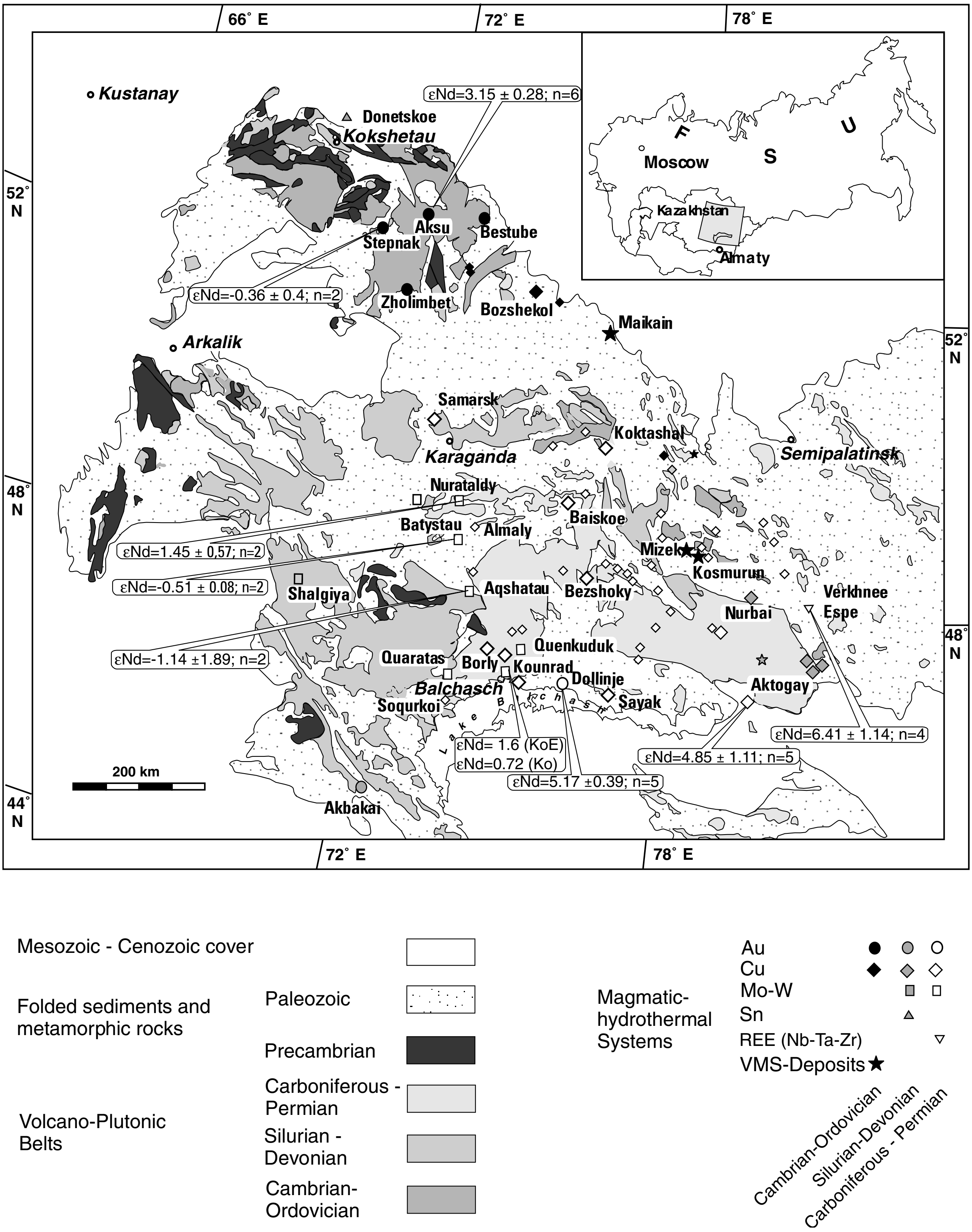
66° E
72° E
78° E
52° N
48° N
44° N
Kustanay
Donetskoe
Kokshetau
εNd=3.15 ± 0.28; n=6
Aksu
Stepnak
Bestube
εNd=-0.36 ± 0.4; n=2
Zholimbet
Bozshekol
Maikain
Arkalik
Samarsk
Karaganda
Koktashal
Semipalatinsk
Nurataldy
εNd=1.45 ± 0,57; n=2
Batystau
Almaly
Baiskoe
εNd=-0.51 ± 0.08; n=2
Shalgiya
Aqshatau
Bezshoky
Mizek
Kosmurun
Nurbai
Verkhnee Espe
εNd=-1.14 ±1.89; n=2
Quaratas
Borly
Quenkuduk
Kounrad
Dollinje
Balchasch
Soqurkoi
Sayak
Aktogay
Lake Balchash
εNd=6.41 ± 1.14; n=4
εNd= 1.6 (KoE)
εNd=0.72 (Ko)
εNd=4.85 ± 1.11; n=5
εNd=5.17 ±0.39; n=5
200 km
Akbakai
F S U
Moscow
Kazakhstan
Almaty
Mesozoic - Cenozoic cover
Folded sediments and metamorphic rocks
Paleozoic
Precambrian
Volcano-Plutonic Belts
Carboniferous - Permian
Silurian - Devonian
Cambrian- Ordovician
Magmatic- hydrothermal Systems
Au
Cu
Mo-W
Sn
REE (Nb-Ta-Zr)
VMS-Deposits
Cambrian-Ordovician
Silurian-Devonian
Carboniferous - Permian

Table 1
Major element (wt%), trace element and rare earth element (ppm) listing of samples of Central Kazakhstan (*total iron; **ppb)

Sample	Rock type	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^*$	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Au deposits													
Aksu													
Ak243	Quartz monzodiorite	55.23	1.00	17.43	7.41	0.11	4.49	7.17	4.27	1.29	0.27	0.82	98.9
Ak245	Porphyritic Granodiorite	64.45	0.59	15.57	4.32	0.08	2.57	4.01	4.49	2.56	0.16	1.78	99.0
Ak246	Hornblende gabbro	49.25	1.24	16.07	8.90	0.13	8.37	9.27	3.41	1.11	0.41	1.58	98.4
Ak248	Quartz monzodiorite	59.55	1.01	16.53	6.16	0.09	2.91	4.18	3.67	2.96	0.35	1.57	97.6
Ak249	Porphyritic Granodiorite	65.58	0.54	15.72	3.75	0.06	2.52	3.57	4.37	2.66	0.17	0.82	99.2
AK39	Granite	67.92	0.43	16.20	3.49	0.04	1.86	3.85	4.59	1.98	0.15	n.d.	100.8
Stepnyak													
ST2	Hornblende gabbro	53.27	1.19	14.55	10.08	0.16	7.86	9.51	2.58	1.34	0.24	1.03	101.8
ST26	Quartz monzodiorite	56.02	0.97	17.46	8.86	0.15	4.60	8.26	3.15	1.54	0.30	0.92	102.2
Dollinye													
Do86	Gabbro	50.81	2.60	16.68	9.42	0.15	6.27	9.29	3.25	0.75	0.26	0.48	99.6
Do87	Porphyritic granodiorite	66.51	0.80	15.26	2.51	0.06	1.73	4.88	5.75	0.57	0.21	0.93	98.4
Do88	Porphyritic monzodiorite	51.83	2.94	16.14	11.54	0.17	2.93	7.51	4.03	1.57	0.87	0.45	99.7
Do89	Quartz diorite	55.38	1.66	16.38	9.05	0.15	4.29	6.87	3.80	1.32	0.29	0.48	99.4
Do90	Quartz diorite	54.92	1.87	14.00	10.18	0.17	5.84	6.76	3.42	1.79	0.42	0.06	99.5
Cu porphyries													
Aqtogay													
AQ1	Porphyritic Granodiorite	64.10	0.68	15.82	6.22	0.11	2.57	5.52	3.22	2.95	0.14	0.83	102.2
AQ3	Granodiorite	61.05	0.73	16.75	6.98	0.13	2.95	6.08	3.18	2.66	0.16	0.94	101.6
AQ4	Granite	69.72	0.51	14.81	4.24	0.08	1.55	3.49	2.72	4.17	0.10	1.22	102.6
AQ7	Porphyry stock	68.52	0.32	16.94	2.92	0.05	0.66	3.12	4.82	3.13	0.11	1.05	101.6
AQ13	Granophyre	68.37	0.37	16.92	2.97	0.08	0.90	2.80	4.78	3.65	0.12	0.86	101.8
Kounrad													
KoG25	Hornblende granodiorite	64.48	0.54	16.14	4.29	0.08	2.19	4.38	4.11	2.25	0.19	0.89	99.5
Rare metal deposits													
Nurataldy													
NurK3	Leucogranite	76.34	0.05	13.20	0.34	0.33	0.03	0.37	4.74	3.91	0.01	0.39	99.7
NurK4	Leucogranite	76.73	0.11	12.80	0.97	0.16	0.19	1.04	3.97	2.11	0.02	1.58	99.8
Aqshatau													
AqsK9	Leucogranite	76.75	0.14	12.15	0.88	0.04	0.10	0.55	3.57	4.96	0.02	0.51	99.7
AQSG3	Leucogranite (contact)	76.91	0.09	12.41	0.34	0.03	0.06	0.80	3.91	4.40	0.02	0.7	99.7
Batystau													
BATG5	Leucogranite (main)	78.41	0.14	11.51	0.65	0.01	0.08	0.33	2.85	5.15	0.02	0.60	99.8
BatG7	Leucogranite	77.41	0.14	12.03	0.71	0.02	0.12	0.57	3.17	5.05	0.03	0.5	99.7
Bektauata													
BekG18	Leucogranite	74.92	0.26	12.94	1.36	0.06	0.22	0.54	3.71	5.13	0.05	0.48	99.7
Kounrad East													
KoeK16	Aplite	76.88	0.10	12.44	0.64	0.03	0.07	0.57	3.84	4.79	0.01	0.38	99.8
REE mineralization Verkhnee Espe													
VE1	Riebeckite granite	78.10	0.07	12.32	2.23	0.05	0.05	0.09	4.81	3.75	0.01	0.56	101.6
VE2	Riebeckite granite	76.86	0.05	12.81	1.94	0.04	0.05	0.08	5.49	3.27	0.01	0.84	100.7
VE3	Riebeckite granite	75.66	0.19	13.37	1.91	0.05	0.10	0.75	4.56	4.72	0.03	0.88	101.5
VE4	Riebeckite granite	76.26	0.05	12.52	2.73	0.07	0.05	0.06	5.25	3.73	0.01	0.93	100.8

Table 1 (*continued*)

Sample	Ba	Rb	Sr	Cs	Li	Ga	Ta	Nb	Hf	Zr	Y	Th	U	Cr	Ni	Co
Aksu																
Ak243	625	25	798	1.1	n.d.	24	n.d.	13	2.08	66	15.3	2.1	0.8	83	59	31
Ak245	1085	37	596	1.1	n.d.	19	n.d.	12	3.23	123	8.7	6.6	2.2	90	40	11
Ak246	462	18	956	428.0	n.d.	21	n.d.	9	2.02	58	16.0	0.5	0.2	335	151	43
Ak248	610	73	99	1.0	n.d.	23	n.d.	15	4.04	104	4.0	21.4	5.8	43	33	14
Ak249	1617	46	788	1.1	n.d.	26	n.d.	7	3.21	131	7.1	6.2	2.4	72	36	13
AK39	1228	40	883	0.6	10.8	22	n.d.	7	2.02	76	6.3	5.3	1.8	61	33	15
Stepnyak																
ST2	246	40	580	1.6	12.0	14	n.d.	7	1.91	55	19.6	5.0	1.0	319	83	41
ST26	812	28	790	1.5	11.7	23	n.d.	5	1.88	60	18.2	3.8	0.8	73	40	24
Dollinye																
Do86	1063	22	452	2.5	n.d.	21	0.9	11	3.01	125	21.5	1.5	0.4	208	102	41
Do87	1327	22	449	1.6	n.d.	17	n.d.	9	7.71	324	32.2	14.8	3.5	22	20	8
Do88	1291	25	374	1.7	n.d.	24	1	29	6.06	254	66.7	3.1	0.9	15	35	35
Do89	1105	31	404	2.9	n.d.	21	n.d.	13	4.99	211	28.9	3.7	1.1	78	44	28
Do90	1119	47	321	1.9	n.d.	13	n.d.	14	6.89	292	44.0	5.0	1.5	172	88	38
Aqtogay																
AQ1	589	69	332	4.7	11.2	12	n.d.	5	4.57	182	20.5	7.5	2.0	45	28	14
AQ3	611	59	465	3.9	11.4	15	n.d.	4	1.46	37	19.4	6.9	1.2	33	17	18
AQ4	670	86	250	4.6	11.7	8	n.d.	2	1.93	61	17.3	12.2	1.6	21	16	10
AQ7	994	33	544	2.4	4.5	23	n.d.	n.d.	1.45	48	4.8	2.1	0.8	5	6	4
AQ13	934	41	369	1.4	5.6	14	n.d.	6	1.43	44	6.2	2.0	0.8	7	13	3
Kounrad																
KoG25	528	69	606	4.1	n.d.	20	0.8	8	2.57	85	11.1	7.7	1.7	24	42	13
Nurataldy																
NurK3	4	590	3	8.3	n.d.	31	13	70	6.87	81	44.7	22.4	14.6	n.d.	42	n.d.
NurK4	214	403	89	15.9	18.0	18	1.2	13	2.57	77	19.7	13.5	5.7	n.d.	38	n.d.
Aqshatau																
AqsK9	34	397	14	10.8	n.d.	22	1.8	26	5.97	148	11.7	60.1	9.0	n.d.	37	2
AQSG3	36.6	543	19.5	11	n.d.	25	2.3	23.0	6.7	137	11.1	48.3	9.2	n.d.	32	n.d.
Batystau																
BATG5	132	373	44	7.8	n.d.	16	1.9	20	3.98	96	19.8	28.0	3.8	n.d.	42	2
BatG7	91.3	357	33.5	7.98	n.d.	15	2.3	22.0	3.7	92.4	18.7	32.6	3.66	n.d.	30	2
Bektauata																
BekG18	225	264	42	5.1	n.d.	20	2	23	3.98	107	31.0	15.0	6.2	n.d.	33	2
Kounrad East																
KoeK16	24	184	22	0.8	n.d.	19	1.3	15	2.54	68	4.1	16.7	5.9	n.d.	29	n.d.
REE mineralization Verkhnee Espe																
VE1	906	357	5	2.5	207.8	31	7.6	98	22.15	999	68.9	13.3	15.4	4	6	n.d.
VE2	16	326	2	2.6	200.3	34	6.2	70	19.13	752	29.9	10.0	10.1	n.d.	12	n.d.
VE3	199	270	87	6.6	97.9	27	4.5	49	11.93	394	88.2	40.2	9.8	n.d.	13	3
VE4	45	421	3	8.2	345.3	31	1.7	27	11.71	256	111.8	12.4	2.3	n.d.	10	3

Table 1 (*continued*)

Sample	Sc	V	Cu	Pb	Zn	Bi	Sn	W	Mo	F	Be	Au**	As	Se	Sb
Au deposits															
Aksu															
Ak243	18	181	119	8.0	68	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	9	3.1	n.d.	0.5
Ak245	7.7	91	48	7.0	33	n.d.	n.d.	n.d.	4	n.d.	n.d.	n.d.	2.1	n.d.	0.5
Ak246	23.6	224	65	4.7	81	0.1	n.d.	n.d.	n.d.	n.d.	n.d.	6	3.1	n.d.	0.6
Ak248	13.4	103	54	19.0	81	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.4
Ak249	7.1	72	56	8.5	30	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3	3.2	n.d.	0.5
AK39	5.6	70	127	7.0	26	n.d.	n.d.	n.d.	5	n.d.	1.32	9	1.6	n.d.	n.d.
Stepnyak															
ST2	32.8	254	69	6.4	87	n.d.	n.d.	n.d.	n.d.	n.d.	1.33	n.d.	3.9	n.d.	0.7
ST26	18.9	200	27	9.6	79	n.d.	n.d.	n.d.	6	n.d.	1.32	n.d.	4.2	n.d.	1.5
Dollinye															
Do86	28	278	96	5.3	69	0.2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	10.6	n.d.	1.2
Do87	10.8	76	75	6.6	20	n.d.	n.d.	n.d.	9	n.d.	n.d.	320	9.7	0.2	4.3
Do88	26.1	272	121	11.0	117	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	5	25.8	0.2	5.3
Do89	22.3	211	210	9.5	89	n.d.	n.d.	n.d.	5	n.d.	n.d.	11	9.7	n.d.	1.6
Do90	26.6	202	136	9.6	84	n.d.	n.d.	n.d.	5	n.d.	n.d.	16	8	0.1	1.8
Cu porphyries															
Aqtogay															
AQ1	19.4	137	58	8.0	50	n.d.	n.d.	n.d.	n.d.	n.d.	0.82	n.d.	18.1	n.d.	0.9
AQ3	20.5	161	66	10.7	92	n.d.	n.d.	n.d.	3	n.d.	0.87	n.d.	9.2	n.d.	0.6
AQ4	12.5	84	87	11.1	126	n.d.	n.d.	n.d.	n.d.	n.d.	0.92	n.d.	9.1	n.d.	0.8
AQ7	2.9	52	51	8.7	27	n.d.	n.d.	n.d.	n.d.	n.d.	1.17	n.d.	7.6	0.4	0.6
AQ13	4.7	67	310	11.7	80	n.d.	n.d.	n.d.	26	n.d.	1.00	n.d.	3.5	n.d.	n.d.
Kounrad															
KoG25	7.9	n.d.	26	12.7	74	n.d.	3	n.d.	n.d.	447	n.d.	n.d.	2.9	n.d.	0.4
Rare metal deposits															
Nurataldy															
NurK3	21.9	n.d.	46	51.1	29	n.d.	8	2	1	768	n.d.	12	n.d.	0.2	n.d.
NurK4	4.4	n.d.	n.d.	20.9	414	n.d.	n.d.	6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.3
Aqshatau															
AqsK9	5.2	n.d.	n.d.	33.5	13	0.7	4	27	6	2195	n.d.	4	n.d.	0.2	0.7
AQSG3	4.3	n.d.	n.d.	18.5	19	1.3	14	20	2	4471	5.00	n.d.	0.8	n.d.	0.7
Batystau															
BATG5	3.1	n.d.	47	32.4	16	n.d.	4	2	3	105	n.d.	n.d.	n.d.	n.d.	0.3
BatG7	3.1	n.d.	90	27.2	14	n.d.	n.d.	n.d.	2	282	0.00	8	0.8	0.3	0.2
Bektauata															
BekG18	3.6	n.d.	98	26.4	51	0.3	4	3	n.d.	963	n.d.	n.d.	4.2	0.2	1
Kounrad East															
KoeK16	2	n.d.	n.d.	28.6	12	n.d.	3	2	2	327	n.d.	7	0.7	0.2	n.d.
REE mineralization Verkhnee Espe															
VE1	1.3	3	3	35.0	253	0.9	n.d.	n.d.	7	n.d.	6.27	n.d.	n.d.	0.5	n.d.
VE2	1.1	4	6	33.2	218	1.4	n.d.	n.d.	n.d.	n.d.	7.76	n.d.	2.1	0.3	n.d.
VE3	3.4	6	4	53.5	110	0.4	n.d.	n.d.	n.d.	n.d.	33.06	n.d.	2.8	0.1	n.d.
VE4	0.9	n.d.	4	22.2	263	n.d.	n.d.	n.d.	n.d.	n.d.	12.22	n.d.	1	0.5	n.d.

Table 1 (*continued*)

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Aksu														
Ak243	16.2	34.8	4.83	19.9	4.44	1.300	4.15	0.553	3.03	0.561	1.550	0.208	1.260	0.192
Ak245	19.0	39.6	4.95	17.8	3.26	0.971	2.59	0.318	1.71	0.314	0.878	0.115	0.787	0.130
Ak246	19.6	44.7	6.28	26.5	5.52	1.670	4.75	0.613	3.38	0.600	1.620	0.209	1.320	0.205
Ak248	17.7	28.9	2.76	8.3	1.19	0.239	0.83	0.105	0.60	0.121	0.389	0.059	0.487	0.079
Ak249	17.5	31.9	3.70	13.2	2.42	0.694	1.92	0.260	1.35	0.264	0.709	0.100	0.679	0.129
AK39	19.8	33.2	3.83	14.3	2.41	0.757	1.51	0.252	1.17	0.240	0.616	0.090	0.595	0.082
Stepnyak														
ST2	13.9	28.3	4.18	18.8	4.49	1.163	2.98	0.657	3.52	0.781	2.001	0.291	1.828	0.236
ST26	22.4	38.7	4.99	21.1	4.55	1.280	3.05	0.626	3.27	0.717	1.870	0.279	1.814	0.240
Dollinye														
Do86	9.9	21.9	3.12	13.8	3.73	1.460	4.29	0.679	3.99	0.792	2.240	0.331	2.030	0.308
Do87	23.6	52.0	6.84	26.8	6.06	1.260	5.88	0.912	5.59	1.100	3.310	0.499	3.280	0.517
Do88	37.0	90.8	12.90	55.9	13.40	3.200	14.80	2.200	12.90	2.530	6.940	0.965	5.990	0.893
Do89	23.6	40.5	5.38	22.2	5.20	1.670	5.50	0.828	5.28	1.070	3.090	0.471	2.920	0.459
Do90	29.0	57.2	7.89	33.1	7.89	1.800	8.52	1.290	8.13	1.640	4.610	0.652	4.250	0.654
Aqtogay														
AQ1	13.7	29.3	3.97	17.5	4.04	0.819	2.71	0.601	3.38	0.794	2.198	0.346	2.311	0.314
AQ3	16.3	33.1	4.43	19.3	4.39	0.992	2.88	0.610	3.35	0.779	2.103	0.329	2.186	0.292
AQ4	13.3	27.4	3.69	15.9	3.60	0.631	2.34	0.512	2.86	0.668	1.870	0.299	1.991	0.269
AQ7	10.7	22.0	2.58	10.7	1.92	0.594	1.20	0.187	0.87	0.184	0.509	0.080	0.551	0.077
AQ13	13.6	25.5	2.94	11.8	2.05	0.571	1.24	0.212	1.05	0.226	0.640	0.102	0.693	0.098
Kounrad														
KoG25	18.5	38.8	4.56	17.8	3.51	0.907	2.52	0.380	2.01	0.405	1.160	0.159	1.140	0.148
Nurataldy														
NurK3	16.3	42.4	5.11	17.4	3.61	0.098	3.11	0.571	4.33	1.080	4.640	1.010	10.300	1.910
NurK4	22.5	46.3	5.08	18.1	3.70	0.653	3.07	0.515	3.17	0.631	1.900	0.301	1.980	0.313
Aqshatau														
AqsK9	64.7	84.2	5.88	14.4	1.86	0.185	1.24	0.212	1.32	0.302	1.220	0.225	2.330	0.488
AQSG3	45.5	53.8	3.44	7.5	0.91	0.090	0.74	0.144	1.01	0.283	1.130	0.241	2.440	0.516
Batystau														
BATG5	40.2	67.2	7.08	22.7	3.71	0.380	2.98	0.456	2.93	0.621	2.090	0.363	2.850	0.443
BatG7	40.6	70.3	6.42	19.7	3.15	0.332	2.53	0.435	2.70	0.607	1.980	0.316	2.670	0.445
Bektauata														
BekG18	44.4	90.4	9.73	34.6	6.80	0.800	5.40	0.931	5.72	1.140	3.290	0.503	3.860	0.581
Kounrad East														
KoeK16	31.9	40.5	2.61	5.7	0.51	0.075	0.35	0.056	0.40	0.097	0.397	0.083	0.743	0.151
REE mineralization Verkhnee Espe														
VE1	54.3	136.8	21.91	75.3	23.62	0.403	14.32	3.270	15.66	3.092	7.764	1.244	8.949	1.221
VE2	26.3	91.0	10.50	39.6	10.02	0.113	5.56	1.231	6.49	1.513	4.690	0.886	6.805	0.973
VE3	50.4	118.6	13.88	52.0	10.80	0.424	6.77	1.700	10.98	2.958	9.149	1.527	9.668	1.226
VE4	62.7	194.3	33.91	137.9	51.71	0.676	35.18	8.472	42.08	7.793	14.686	1.414	7.524	0.970

Table 2
Rb-Sr and Sm-Nd isotope data of Central Kazakhstan samples. SiO_2 in weight%, Rb, Sr, Nd and Sm in ppm. $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ are corrected measured ratios; $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ are measured ratios normalized to $^{146}Nd/^{144}Nd = 0.7219$; i $^{143}Nd/^{144}Nd$ is the initial isotopic composition calculated using idealized crystallization ages (Age, last column). $\varepsilon Nd = ((_i{}^{143}Nd/^{144}Nd)/(_{CHUR\ at\ Age}{}^{143}Nd/^{144}Nd) - 1)^* 10^4$, calculated using present day values for CHUR: $^{143}Nd/^{144}Nd = 0.512638$; $^{147}Sm/^{144}Nd = 0.1966$. D.M are depleted mantle model ages based on the model of DePaolo (1981). $^* = {}^{147}Sm/^{144}Nd$ too high for D.M. calculation

Sample	Rock type	SiO_2	Rb	Sr	$^{87}Rb/^{86}Sr$	$_{87}Sr/_{86}Sr$	Nd	Sm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$^{143}Nd/^{144}Nd$	ε_{Nd}	D.M.	Age
Au deposits														
Aksu														
Ak243	Quartz monzodiorite	55.23	25	772	0.09489	0.70505	19.9	4.44	0.133545	0.512631	0.512237	3.49	789	450
Ak245	Porphyritic Granodiorite	64.45	36	597	0.17356	0.70546	17.8	3.26	0.111101	0.512546	0.512219	3.13	744	450
Ak246	Hornblende gabbro	49.25	16	953	0.04941	0.70475	26.5	5.52	0.125261	0.512573	0.512204	2.83	814	450
Ak248	Quartz monzodiorite	59.55	72	445	0.47121	0.70754	8.3	1.19	0.125442	0.512609	0.512239	3.53	756	450
Ak249	Porphyritic Granodiorite	65.58	46	841	0.15599	0.70545	13.2	2.42	0.111325	0.512546	0.512218	3.12	746	450
AK39	Granite	67.92	42	898	0.13496	0.70635	0.8	1.51	0.104472	0.512511	0.512203	2.82	748	450
Stepnyak														
ST2	Hornblende gabbro	53.27	41	594	0.20207	0.70809	18.8	4.49	0.143830	0.512485	0.512061	0.04	1208	450
ST26	Quartz monzodiorite	56.02	29	797	0.10372	0.71277	21.1	4.55	0.131066	0.512406	0.512020	-0.76	1167	450
Dollinye														
Do86	Gabbro	50.81	20	428	0.13462	0.70435	13.8	3.73	0.157826	0.512846	0.512536	5.54	563	300
Do87	Porphyritic granodiorite	66.51	21	455	0.13527	0.70541	26.8	6.06	0.134055	0.512747	0.512483	4.52	583	300
Do88	Porphyritic monzodiorite	51.83	40	365	0.31246	0.70472	55.9	13.40	0.144052	0.512818	0.512536	5.54	522	300
Do89	Quartz diorite	55.38	33	395	0.24194	0.70502	22.2	5.20	0.140946	0.512782	0.512505	4.95	565	300
Do90	Quartz diorite	54.92	49	304	0.46066	0.70551	33.1	7.89	0.144792	0.512809	0.512524	5.32	539	300
Cu porphyries														
Aqtogay														
AQ1	Porphyritic Granodiorite	64.10	72	305	0.68139	0.70964	17.5	4.04	0.139797	0.512812	0.512538	5.58	498	300
AQ3	Granodiorite	61.05	63	430	0.42747	0.70798	19.3	4.39	0.137843	0.512750	0.512480	4.45	603	300
AQ4	Granite	69.72	87	252	0.99784	0.71380	15.9	3.60	0.137114	0.512798	0.512529	5.41	508	300
AQ7	Porphyry stock	68.52	31	686	0.13129	0.70622	10.7	1.92	0.119443	0.512633	0.512399	2.86	672	300
AQ13	Granophyre	68.37	46	536	0.24723	0.70710	11.8	2.05	0.094929	0.512743	0.512556	5.94	403	300
Kounrad														
KoG25	Hornblende granodiorite	64.48					17.8	3.51	0.112681	0.512496	0.512257	0.72	828	325
Rare metal deposits														
Nurataldy														
NurK3	Leucogranite	76.34					17.4	3.61	0.097924	0.512529	0.512317	2.03	684	330
NurK4	Leucogranite	76.73					18.1	3.70	0.107405	0.512491	0.512258	0.88	797	330
Aqshatau														
AqsK9	Leucogranite	76.75					14.4	1.86	0.069635	0.512427	0.512290	0.75	658	285
AQSG3	Leucogranite (contact)	76.91					7.5	0.91	0.101173	0.512296	0.512097	-3.03	1010	285

Table 2 (*continued*)

Sample	Rock type	SiO_2	Rb	Sr	$^{87}Rb/^{86}Sr$	$_{87}Sr/_{86}Sr$	Nd	Sm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$^{143}Nd/^{144}Nd$	ε_{Nd}	D.M.	Age
Batystau														
BATG5	Leucogranite (main)	78.41					22.7	3.71	0.092866	0.512397	0.512209	-0.59	818	310
BatG7	Leucogranite	77.41					19.7	3.15	0.077448	0.512374	0.512217	-0.43	753	310
Bektauata														
BekG18	Leucogranite	74.92					34.6	6.80	0.130491	0.512558	0.512310	0.89	890	290
Kounrad East														
KoeK16	Aplite	76.88					5.7	0.51	0.050081	0.512438	0.512341	1.62	572	295
REE mineralization Verkhnee Espe														
VE1	Riebeckite granite (sub)	78.10					75.3	23.62	0.064324	0.512824	0.512719	7.86	243	250
VE2	Riebeckite granite	76.86	310	2.37	438.59517	2.34027	39.6	10.02	0.101185	0.512850	0.512684	7.19	286	250
VE3	Riebeckite granite	75.66	268	55	14.13595	0.77342	52.0	10.80	0.086496	0.512731	0.512589	5.33	391	250
VE4	Riebeckite granite	76.26					137.9	51.71	0.224270	0.512954	0.512587	5.28	*	250

These relatively low values contradict a derivation from the about 2 Ga old continental material represented by the Kokshetav massif, that was virtually flooded by the Zerenda granites. The low initial Sr ratio is in agreement with our initial $^{87}Sr/^{86}Sr$ from a 428 ± 9 Ma Rb–Sr mineral isochron on the second-phase granite of the Krykkuduk complex of 0.70539 ± 11, as well as with our whole-rock isochron on magmatic rocks of the Aksu gold deposit, which gave an age of 467 ± 27 Ma with an initial $^{87}Sr/^{86}Sr$ of 0.7042 ± 7 (Heinhorst, in preparation). See also the positive ε Nd values of the Aksu system (Table 2; Fig. 7).

The setting of the younger gold deposits of Akbakai and Dollinye in southern Kazakhstan is very similar, but there intrusive magmatism started only in the Devonian and Carboniferous, respectively. However, both the northern and southern Kazakhstan gold deposits are close to outcrops of ophiolites of Cambrian to Early Ordovician age.

3.2. Copper porphyries

Copper porphyries developed throughout the Paleozoic evolution of Central Kazakhstan, with a maximum in the Carboniferous. The main intrusive phases are represented by coarse-grained biotite-hornblende granodiorite. These rocks have 35–40% plagioclase (andesine–oligoclase), 20–30% K-feldspar, 10–20% quartz, and up to 20% biotite and hornblende. Subsequent phases are diorites, medium-grained granodiorite and porphyritic granodiorite, and are very often affected by strong alteration. Mafic intrusive units are much less developed in the rock suite associated to copper porphyries compared to the rock spectrum in association with the mesothermal gold deposits.

The oldest known deposit of Bozchekul to the north of Central Kazakhstan is accompanied by diorite to tonalite plutons and dikes, which cut Cambrian mafic volcanics. A mineral Rb–Sr isochrone on tonalite yielded 481 ± 23 Ma, with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70387 ± 14 (Kudryavtsev, 1996). The Bozshekol deposit belongs to a later stage of the earliest narrow linear oceanic island arc system, that was accreted in the Ordovician by horizontal stacking along major strike-slip shear zones (Sengör et al., 1993). Major tectonic inversions typically control the temporal distribution of Cu-porphyry formation and it is implied that the Bozchekul deposit marks the onset of island-arc stacking, leading to the formation of a continental crust precursor.

The recently explored deposit of Samarskoye is an example from the Devonian magmatic arc. Country rocks with red molasse beds and ash-flow tuffs document progressively continental conditions. At Samarskoye, the mineralization is hosted by subvolcanic quartz monzonite stocks intruding an earlier phase of more deep-seated quartz diorites.

The Carboniferous deposits (Kounrad, Sayak, Aqtogay, Borly, etc.) are confined to large granodioritic batholiths in a thick continental crust pile that had accumulated along repeated periods of sedimentation, volcanism and orogenesis from Ordovician to Carboniferous. Tectonic setting and the typical pervasive alteration style are similar to the classic Mesozoic examples from the western mountain chains of North and South America.

For the Carboniferous Cu porphyries of Central Kazakhstan a Rb–Sr mineral isochron of the Aqtogay deposit exists for an earlier host rock with lower crust xenoliths, which gave an age of 366 ± 10 Ma at an initial $^{87}Sr/^{86}Sr$ value of 0.70345 ± 8. The melanocratic xenoliths were treated separately for Sm–Nd isotopic mineral compositions, yielding an age of 359 ± 43 Ma at an initial εNd of 5.9 (Ermolov, 1996).

3.3. Molybdenum porphyries

Molybdenum ore deposits of Central Kazakhstan, often with major tungsten resources, are restricted to the widespread Upper Carboniferous leucogranite magmatism subsequent to granodiorite batholith formation. Emplacement of these late orogenic felsic melts is commonly controlled by pull-apart structures connected to strike-slip shear-zones. Leucogranites occur also during subsequent stages of the Devonian magmatic arc, but associated rare-metal mineralization is confined to the west and north (Donetskoye tin deposit) of Central Kazakhstan, where old crystalline basement such as the Kokshetav massif was affected by Devonian magmatism. Similarly, the Carboniferous leucogranites have a much higher ore potential where the Carboniferous arc is superimposed on Devonian and Ordovician arcs, terrains where the

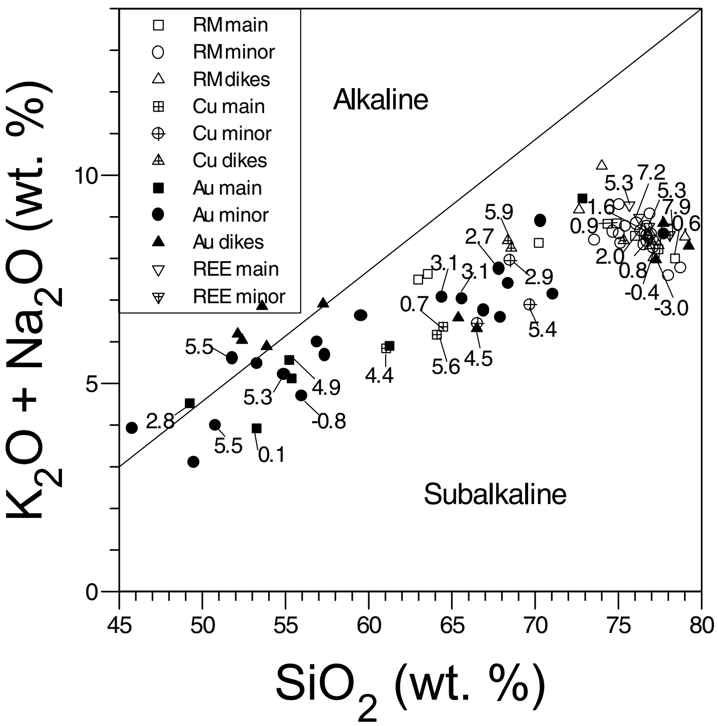

Fig. 2. Alkalies versus silica variation plot for sample suite studied. Numbers refer to initial εNd values. Rock classification according to related mineralization (RM = rare-metal granites, i.e. Mo, W, Be, Sn; Cu = copper porphyries; Au = mesothermal gold systems; REE = peralkaline granites with REE–Zr–Nb mineralization).

basement also was affected earlier by ultra-metamorphism and melt extraction. These conditions were described as “tectono-magmatic reactivation” (Serykh, 1996).

The leucogranites with Mo porphyry mineralization, although invariably of leucocratic alkali feldspar granite composition, comprise a large range of textures from equigranular, coarse-grained to aplitic, to porphyritic up to two-phase granite, i.e. large phenocrysts of feldspars, quartz and biotite set in a very fine-grained groundmass. Perthitic K-feldspar and oligoclase-albite have about equal amounts of 30% each, quartz makes up to 30–40%, and biotite is around 1–2%. Accessory minerals include magnetite, titanite, zircon, monazite, allanite, apatite and, sporadically, ilmenite. Fluorite and garnet porphyroblasts, found in a few samples, are considered to be of postmagmatic origin.

Rb–Sr isotope data on leucogranites of the Central Kazakhstan molybdenum province are available through a study by Negrej et al. (1991) who found initial $^{87}Sr/^{86}Sr$ values of 0.7059 ± 3 (Akshatau), 0.7050 ± 1 (Qaldirma) and 0.7073 ± 6 (Qyzyltau West).

3.4. REE–Zr–Nb mineralization

The REE–Zr–Nb mineralization of eastern Central Kazakhstan is related to a narrow belt of Permian high-silica riebeckite-aegirine granites which extends over 2000 km from Kazakhstan over North-West China to South Mongolia. The Verkhnee Espe is one of the largest occurrences of REE–Nb–Zr mineralization along this belt and is situated at the contacts of two riebeckite granite cupolas with their sedimentary host rocks. The ore material consists of both pegmatite veins and metasomatic replacement lodes with a variety of rare minerals of Zr, Nb, and REE.

The Verkhnee Espe mineralization is associated to a leucocratic multiple granite intrusion composed of

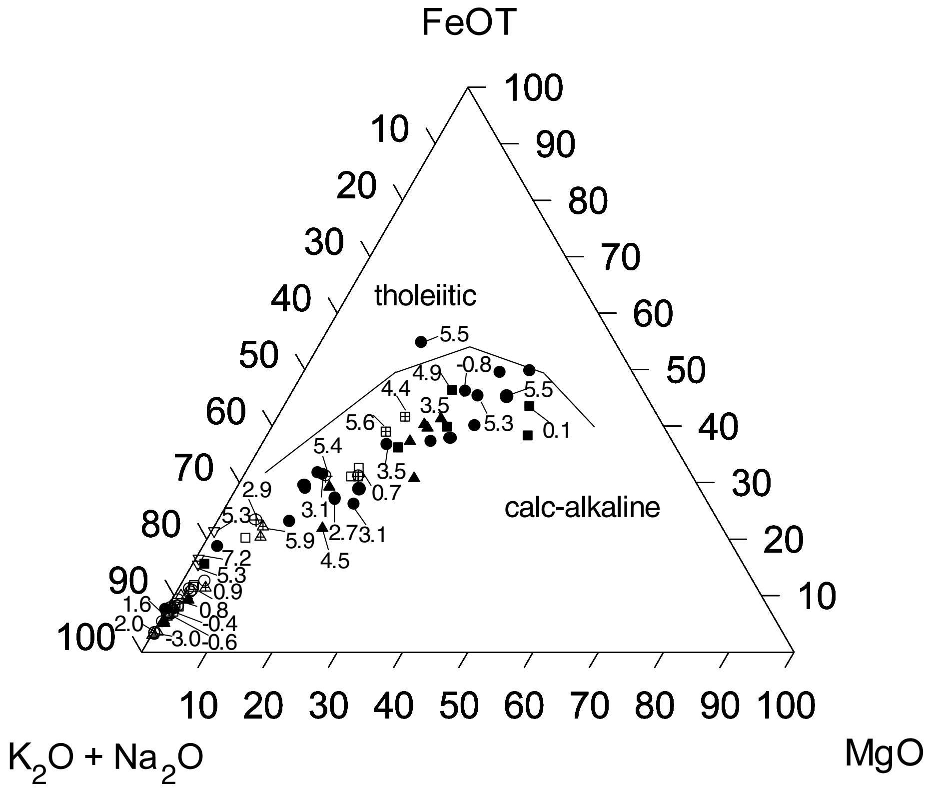

Fig. 3. AFM triangle plot for Central Kazakhstan sample suite. For symbol explanation see legend in Fig. 2.

riebeckite, riebeckite–biotite and riebeckite–aegirine granite units. The medium- to coarse-grained equigranular rocks have variable ratios of their main felsic minerals consisting of microcline-perthite, quartz (20–50%) and albite. Albite occurs as both primary, and postmagmatic phases, with the postmagmatic variety rising up to 50%, depending on degree of postmagmatic alteration. Riebeckite is the predominant mafic mineral in amounts of 3–8%, accompanied by variable proportions of aegirine, biotite and rare astrophyllite. Zircon, pyrochlore, rutile, titanite, xenotime were identified as accessory phases. Minor dike rocks have a similar mineralogy but have porphyritic textures with phenocrysts of K–Na feldspar, quartz and riebeckite.

3.5. Geochemical data

Although comprising a large variety of timing, localities, tectonic settings and mineralogies of magmatic rocks, a number of element correlations were found to be coherent throughout the sample set (Table 1). The alkalies versus silica diagram (Fig. 2) shows a relatively narrow band of compositions of normal to slightly elevated alkalinity, below the alkaline/subalkaline divide (Irvine and Baragar, 1971). The samples define an extended calcalkaline trend on the AFM triangle (Fig. 3), with only one exception of a mafic dike from the gold deposit of Dollinye plotting in the tholeiitic field. The K_2O versus SiO_2 plot (Gill, 1981) further shows almost all samples to be of high-K affiliation (Fig. 4).

The A/CNK versus A/NK diagram (Maniar and Piccoli, 1989) defines the rocks as metaluminous to only slightly peraluminous, and of I-type character (Fig. 5). In the conventional Pearce diagram (Pearce et al., 1984) most samples plot into the volcanic-arc field (diorites to granodiorites) with an extension into the syncollisional field (leucogranites) (Fig. 6). Exceptions are the riebeckite granites associated to REE–Nb mineralization and a few mafic samples

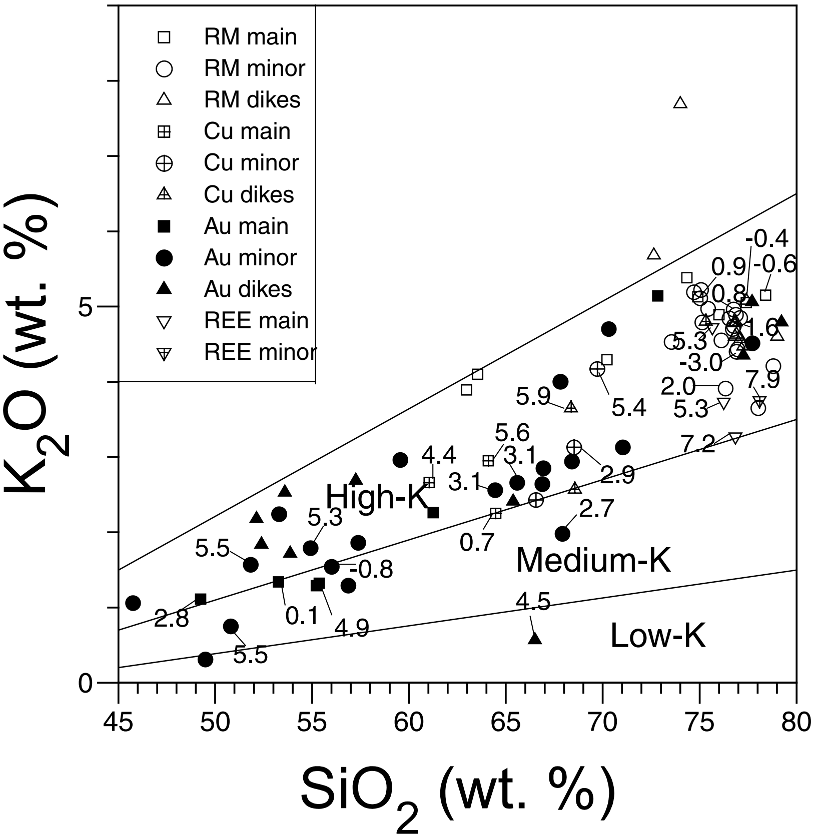

Fig. 4. Potassium versus silica variation plot. For symbol explanation see legend in Fig. 2.

from the gold deposits of Dollinye and Akbakai which have higher contents of high-field strength elements (Y + Nb).

The sample set represents rocks belonging to the high-K calcalkaline series of I-type character. This fact is obviously caused by the biased sampling strategy focussing on ore-related magmatism and is an expression of the generally higher ore potential of this series in comparison to other rock series, which are also developed in Central Kazakhstan (Serykh, 1996).

The compositional variations within the sample set are not continuous, but show a distinct grouping, corresponding to gabbroic, dioritic, granodioritic and granitic compositions, respectively (Figs. 2–6).

Sr and Nd isotope data are given in Table 2. Sr isotope determinations were not successful in certain cases of samples of leucogranite, where Rb/Sr ratios were too high. The sample set from Aksu (gabbro to granodiorite) defines a 5-point isochron age of 467 ± 27 Ma with an initial $^{87}Sr/^{86}Sr$ of 0.7042 ± 7. This result confirms the earlier data from Shatagin (1994).

The Nd isotopic variations in the sample set are surprisingly small, in spite of the large variety of rock types and ages. Most εNd values are positive, only a few are slightly negative, and show no correlation with the geochemistry of the samples (Fig. 7). Note that εNd values are consistent for individual intrusive suites in spite of a large variation in silica.

The Ordovician gabbro to granodiorite sequence from Aksu (host to mesothermal gold mineralization) has a very narrow εNd range of +2.8 to +3.5. The other Ordovician gold-related gabbro to quartz diorite sequence from Stepnyak has an εNd range of 0 to −0.8, which is thought to reflect the setting at the border of the Proterozoic/Archean Kokchetav Massif. The similar magmatic rock sequence at the

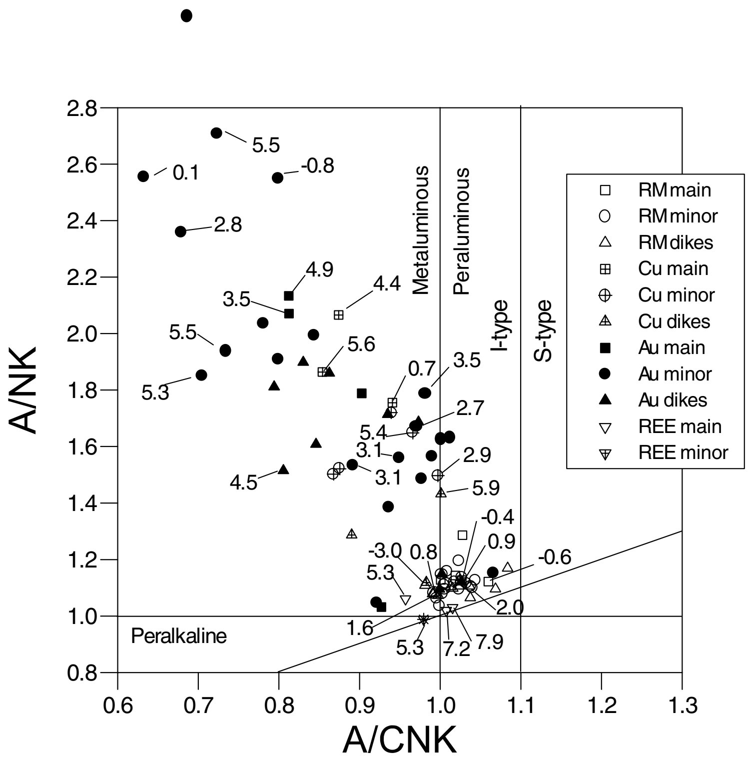

Fig. 5. Molar ratios of alumina/calcium + sodium + potassium versus alumina/sodium + potassium.

Carboniferous gold-deposit Dolinnje is situated near Lake Balkash, in the central part of the inward younging oroclinal bend, and has an εNd range of +4.5 to +5.5. The Carboniferous copper porphyry systems of Kounrad and Aqtogay have εNd values of +0.7 and +2.9 to +5.9.

The Upper Carboniferous to Permian molybdenum-bearing granites from Nurataldy, Aqshatau, Batystau and Bektauata display εNd values of -0.6 to +2.0. The exceptionally low εNd value of one sample from Aqshatau (−3.0) represents a border facies of the leucogranite and probably results from contamination with sedimentary country rocks.

The Permian peralkaline riebeckite granites from Verkhnee Espe (REE–Nb–Zr-mineralization) have εNd values of +5.3 to 7.9. These are the only samples for which crystallisation ages are in line with their depleted mantle model ages. The samples of magmatic rocks of the other deposit types have depleted mantle model ages which are 200–300 Ma older than their intrusion ages (an exception are the two Stepnyak samples with their setting at the border of the Precambrian Kokshetav Massif). Mantle extraction ages calculated according to the depleted mantle model of DePaolo (1981) are typically around 300 Ma higher than the actual ages (K–Ar) of the sampled rocks, except for samples of Verkhnee Espe, where model- and real ages coincide.

4. Geodynamic conclusions

The positive εNd values, which were found throughout rock types of a wide temporal and spatial range, exclude a significant contribution of ancient continental crust material as source or contaminant to the long-lasting subduction-coupled magmatism of Central Kazakhstan. The depleted-mantle model ages coincide with the age of the Vendian rift, that formed a back-arc ocean along the margin of the Angara–Baltica supercontinent as a consequence of the start-up of subduction at that time, and we assume that the lower crust of Central Kazakhstan is probably derived from this Vendian oceanic crust.

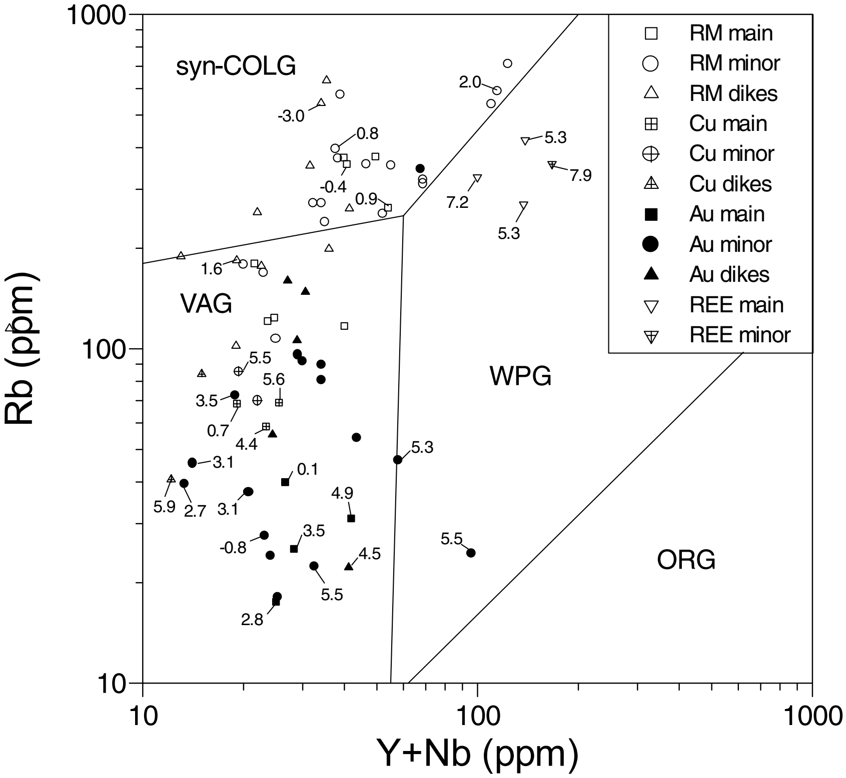

Fig. 6. Yttrium + niobium versus rubidium tectonomagmatic discrimination diagram according to Pearce et al. (1984).

This result contradicts geotectonic models which assume an ancient continental basement for the whole area. On the other hand, the volcano-sedimentary record documents that continental conditions prevailed since the Ordovician and that the younger magmatic arcs are superimposed on each other in a continental setting. It seems that growth of the continental crust since the Ordovician was not accomplished by the accretion of island arcs, but by active continental margin magmatism. The active continental margin magmatism must have transformed the former back-arc oceanic crust into the present lower continental crust by burial with magmatic and sedimentary material, recurrent high-grade metamorphism, basaltic melt injection/underplating, and granitic melt extraction. The lack of the Vendian/Lower Cambrian age imprint of the samples of Verkhnee Espe probably reflects the rifting related nature of this magmatism at the onset of the platform stage after cessation of subduction. Only in this situation, subsequent to the long-term differentiation and final cooling of the lower crust of Central Kazakhstan, magmas could rise and differentiate without a significant contribution of Vendian/Cambrian lower crust material. The very high positive εNd values of the anorogenic rift-related Permian peralkaline riebeckite granites may instead be inherited from very young subcrustal lithosphere at the mantle/crust boundary that was affected by partial remelting due to asthenospheric upwelling during rifting.

The importance of Phanerozoic crustal growth has only recently been recognized by isotopic characterization of modern and Paleozoic orogenic terranes like the Lachlan fold belt of Australia and the Appalachian orogen of North America (Samson et al., 1995; Blevin and Chappell, 1995). These terranes comprise both a similar range of εNd values of $+2$ to $+5$ and a similar metallogenic spectrum as Central Kazakhstan.

The large-scale processes associated with crust

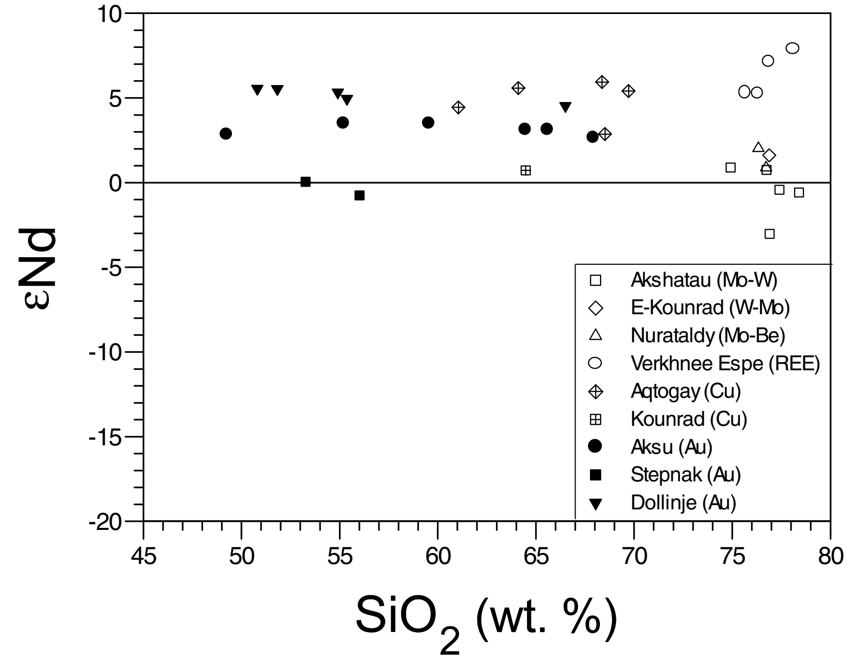

Fig. 7. Silica versus initial εNd variation plot.

formation and differentiation controlled by subduction are probably the most favorable environments for the generation of magmatic-hydrothermal ore deposits. However, the largely juvenile nature of Central Kazakhstan contrasts with Cordilleran or Andean settings in which Proterozoic lower crust is often present. The major contribution of this older crustal material to magmatism is reflected by ubiquitously negative εNd values and high initial $^{87}Sr/^{86}Sr$, a typical feature of the felsic rocks of the Laramide and earlier orogenies which host a number of important Cu and Mo porphyry deposits in the western USA (Barton, 1990; Lang and Titley, 1998).

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