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A new look at the Altaids: A superorogenic complex in northern and central Asia as a factory of continental crust. Part II: palaeomagnetic data, reconstructions, crustal growth and global sea-level

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Nature is not more complicated than you think.
It is more complicated than you can think.
Frank Edwin Elger

Abstract

The Altaids, an Ediacaran to early Cretaceous superorogenic complex in central and northwestern Asia, is bounded on the west by the Urals, on the south by the 'Intermediate Units' consisting of the Alay Microcontinent, the Tarim Block and south China carrying also the Manchuride Orogenic Belt and on the northeast by the Siberian Craton. Within this frame the superorogenic system evolved along two major arc systems, both in part rifted from the Siberian Craton. Throughout the evolution of the system there were no continental or arc collisions until the system was sealed by its final collision with the intermediate units in the late Palaeozoic and the closure of the Khangai-Khantey Ocean during the early Cretaceous. Available reliable palaeomagnetic data are consistent with the operation of only two major arc systems throughout the evolution of the superorogenic complex. During this evolution the Altaids seem to have generated some 3 million km^2 new continental crust which comes to some 0.5 km^3 annually. This is about one-third of the average rate of growth of the continental crust. The global eustatic sea-level seems to have been dominated by the Altaid evolution only during the latest Carboniferous and the early Permian.

1. Introduction

In the first part of this paper (Şengör et al., 2014) we reviewed the available geological data on the entire Altaid superorogenic system of central and northwestern Asia (Fig. 1) supported by some 1090 new, mostly zircon ages of magmatic and some metamorphic rocks. It is the purpose of this second part to present all the available reliable palaeomagnetic data and then relate the evolution of the entire system in terms of fifteen time-lapse frames of reconstructions from the Ediacaran to the early Cretaceous. In what follows, we first outline how we selected the palaeomagnetic data and how they were treated while building the reconstructions. We then review the basic principles of the reconstruction. This had been done before in Şengör et al. (1993) and Şengör and Natal'in (1996), but we repeat it here and enlarge upon the earlier account in view of the new palaeomagnetic data and the objections raised subsequently in the literature to the earlier account. The new account contains some interesting observations on the nature of the interpretations of palaeomagnetic results in complexly deformed areas of wide extent and diffuse strain. We basically conclude that the objections against the evolutionary model presented in Şengör et al. (1993) and Şengör and Natal'in (1996) have mostly resulted from either misunderstanding of what had been said or of the consequences of the alternatives proposed.

Last, we present the reconstructions. For each time frame, with the exception of the Mesozoic ones, we show two maps: one with the units identified and palaeomagnetic observations points shown and the other with the newly-dated igneous and metamorphic rocks indicated on the maps. We have been forced to use two maps for each time slice, simply because otherwise the maps would have become illegible owing to overcrowding of symbols. We emphasise at the outset that our reconstructions, although they represent serious improvements upon those in Şengör and Natal'in (1996), are most likely still substantially wrong in terms of the shape of the Kipchak Arc and the geometry of the southern wing of the Tuva-Mongol Arc, simply because reliable palaeomagnetic data are so sparse. The main advantage of the reconstructions we offer is that they indicate where more observations are needed.

2. Palaeomagnetic data selection

Palaeomagnetic data were compiled with the following constraints: ages are restricted to Palaeozoic plus earliest Triassic (542 – 242 Ma) for the Altaids and neighbouring areas (latitude range 37.2-54.3°N, and longitude range 66.6-119.4°E) from the generally accessible literature (published after 1992), and containing palaeomagnetic results obtained with modern laboratory treatments and important field tests, including principal-component analysis, reversal (r), fold (f), conglomerate (cg), and baked contact (bc) tests. These tests, when “negative” are exceedingly useful to allow identification of undesirable magnetizations that are younger than the hosting rocks. The selected results are listed in Table 1, ranked by age of the rocks that reveal a characteristic, and presumably primary, magnetization. In other words, remagnetizations have not been included. Imprecise age assignments may have disqualified certain poorly dated palaeomagnetic results. About 4, otherwise qualifying results, have been listed in the table as “not used” for additional reasons specified at the bottom of the table (## 1 – 4). A few additional palaeomagnetic results, published by Russian authors (e.g., Burtman et al., 1998; Grishin et al., 1997; Klishevich and Khramov, 1993) are in broad agreement with the results listed in the table, but have not been included because they lack relevant detailed information.

3. Methodology followed in building the reconstructions

These reconstructions are all made on the basis of the geological data discussed in Part I (Şengör et al., 2014), palaeomagnetic data discussed above, and in some cases sparse palaeobiogeographical data. In nearly all cases we allowed no error margin to the palaeomagnetic data as reported in Table I and honoured both the palaeolatitude reported and the orientation. The relative positions of continents along the latitudes we determined only as dictated by regional geology, frequently ignoring the positioning suggested by our sources listed above, for most had little structural geological basis.

Positions of the Russian and Siberian cratons as well as Tarim and North China blocks are shown as suggested by Cocks and Torsvik (2005) for Ediacaran times, by Torsvik et al. (2014) for early Cambrian, late Cambrian, medial and late Silurian-early Devonian, late Devonian, early Carboniferous, late Carboniferous, early Permian and late Permian, and by Torsvik and Cocks (2013) for the medial Ordovician and late Ordovician) with small changes well within the error margins

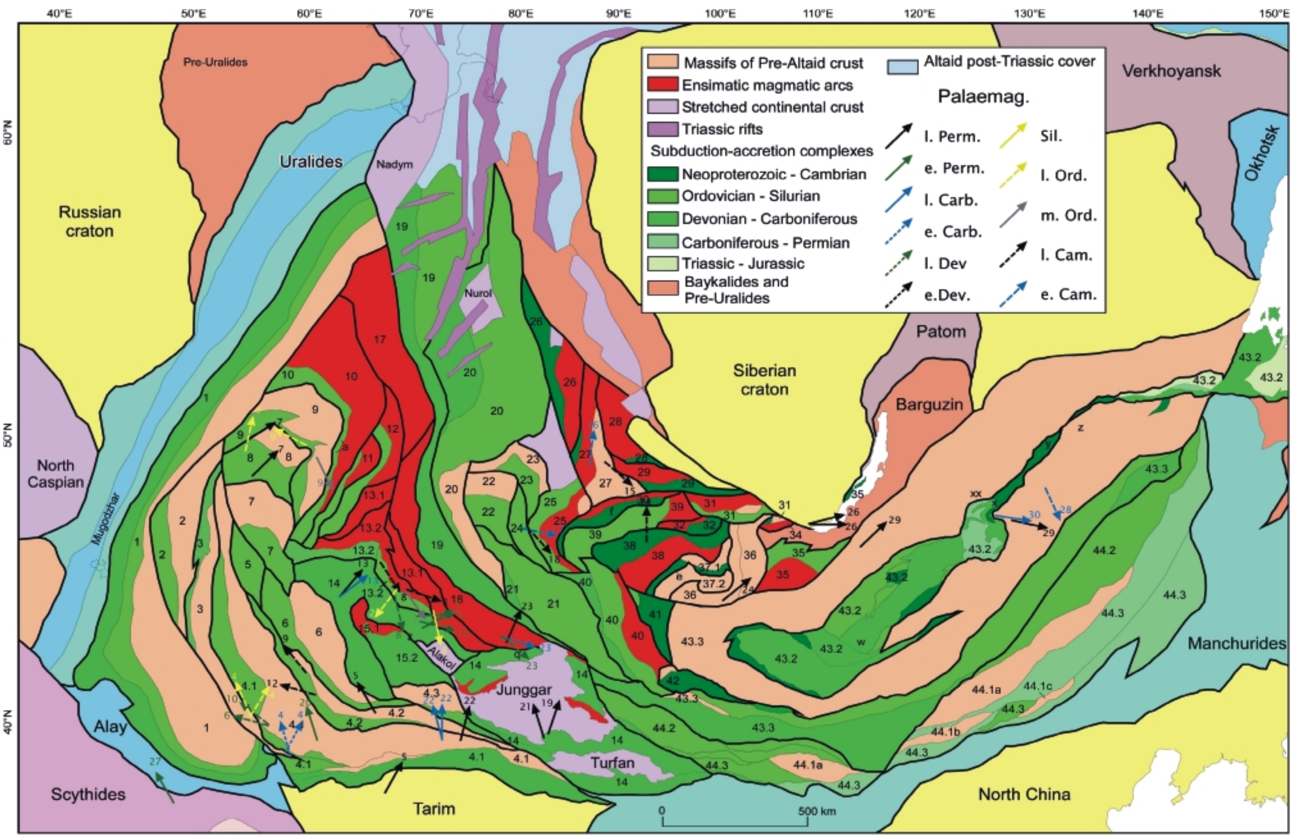

Figure 1: Tectonic map of the Altaids. The map is based on a equidistant conical projection with the central meridian is 95° and the standard parallels are 1:15.0 and 2:85.0, latitude of origin is 30.0. It is essentially the same as the map in Fig. 6 of the first part of this paper (Şengör et al., 2014), except that the ophiolite occurrences are removed and the palaeomagnetic declination vectors are added. The numbers at the tips of the palaeomagnetic vectors are those of reference numbers in Fig. 1. The Arabic numerals and the lower case letters attached to some of them correspond with the first-order tectonic units of the Altaids. *Key to the first-order tectonic units:* 1. Valerianov-Chatkal, 2. Turgay, 3. Baykonur-Talas, 4.1 Djezkazgan-Kirgiz, 4.2 Jalair-Naiman, 4.3 or 16. Borotala, 5. Sarysu, 6. Atasu-Mointy, 7. Tengiz, 8. Kalmyk Kol-Kökchetav, 9. Ishim-Stepnyak, 10. Ishkeolmes, 11. Selety, 12. Akdym, 13.1 - Boshchekul-Tarbagatay, 13. 2 - Bayanaul-Akbastau, 14. Tekturmas, 15. Junggar-Balkhash, 16 or 4.3. Borotala, 17. Tar-Muromtsev, 18. Zharma-Saur, 19. Ob-Zaisan-Surgut, 20. Kolyvan-Rudny Altay, 21. Gorny Altay, 22. Charysh-Chuya-Barnaul, 23. Salair-Kuzbas, 24. Anuy-Chuya, 25. Eastern Altay, 26. Kozhykhov, 27. Kuznetskii Alatau, 28. Belyk, 29. Kizir-Kazyr, 30. North Sayan, 31. Utkhum-Oka, 32. Ulugoi, 33. Gargan, 34. Kitoy, 35. Dzhida, 36. Darkhat, 37. Sangilen, 38. Eastern Tannuola, 39. Western Sayan, 40. Kobdin, 41. Ozernaya, 42. Han-Taishir, 43. Tuva-Mongol (43.1. Tuva-Mongol Arc Massif, 43.2. Khangay-Khantey, 43.3. South Mongolian, 44. South Gobi.

Unit Name	Unit No	Lat.	Lon.	Age	Age (Ma)	Ref.	Dec.	Inc. (°)	Inc. (rads)	a95	Tests	Paleolat (rads)	Paleolat (rads)
North-Ishim-River-Pu	unit 8	52.9	66.6	Late Perm.	245	7	55.9	69.1	1.21	4.2	r	0.92	52.6
Junggar, Heavenly Lake Sec.	unnit 14	44.0	88.1	Late Perm.	251	19	18.0	59.0	1.03	13.0		0.69	39.8
NTZ-BO, KP, KB	unit 4.2	44.0	78.3	Late Perm.	255	5	330.5	47.5	0.83	12.0	f	0.50	28.6
NTZ-SH	Tarim	41.0	79.7	Late Perm.	255	5	28.2	40.3	0.70	13.2		0.40	23.0
North-Teniz-Basin-Tr	unit 8	51.7	67.8	Late Perm.	255	7	44.3	56.8	0.99	2.7	f	0.65	37.4
Junggar, Lucaogou Fm.	unit 14	43.8	87.7	Late Perm.	260	21	343.0	61.9	1.08	4.0	f	0.75	43.1
Trans-Baikal, Borzya, Belektuy	unit 43.1	50.7	116.9	Late Perm.	260	29	102.8	37.4	0.65	13.8	f, r	0.37	20.9
Trans-Baikal, Khilok, Alentuy	unit 43.1	50.8	107.2	Late Perm.	260	29	45.2	76.2	1.33	8.1		1.11	63.8
SWTien Shan, Luchob Fm.	Alay micro	38.9	68.9	Mid. Perm.	280	27	325.0	39.0	0.68	4.9	f	0.38	22.0
Chingiz-Ayaguz-A1	unit 14	47.8	79.9	Mid. Perm.	280	1	84.9	50.2	0.88	4.8	f	0.54	31.0
Chingiz-Ayaguz-B	unit 14	47.4	80.3	Mid. Perm.	280	1	57.0	47.9	0.84	3.4		0.51	29.0
NTZ, Kirghiz Range, Issyk-Kul	unit 4.1	42.5	75.5	Mid. Perm.	284	20	343.0	48.0	0.84	6.1	f	0.51	29.0
Chingiz-Ayaguz-A2	unit 14	47.6	80.1	Mid. Perm.	290	13	105.2	50.5	0.88	6.3	cg	0.55	31.2
Tokrau-A	unit 14	48.0	75.0	Late Carb.	295	13	51.5	40.0	0.70	4.3	f, r	0.40	22.8
Yili, Zhaosu	unit 4.1	43.3	82.3	Late Carb.	310	22	0.2	40.9	0.71	13.6		0.41	23.4
Yili, Xinyuan	unit 4.1	43.3	82.3	Late Carb.	310	22	345.3	36.4	0.64	11.0		0.35	20.2
Junggar NW, Saur Ridge	unit 18	47.4	85.0	Late Carb.	310	23	107.5	56.5	0.99	4.8	f	0.65	37.1
NTZ-Dungurma	unit 4.1	41.7	74.3	Early Carb.	330	4	344.1	31.2	0.54	6.4	f	0.29	16.8
NTZ-Tabylgaty-B	unit 4.1	41.7	74.0	Early Carb.	340	4	27.6	28.3	0.49	5.2	f	0.26	15.1
NTZ-Frasnian-Aral-2	unit4.1	42.6	72.7	Late Dev.	375	10	308.7	42.7	0.75	4.3	r, f, cg	0.43	24.8
Chingiz-Kurbakanas-KU	unit 13.2	48.3	78.3	Late Dev.	380	8	167.0	44.3	0.77	7.8	r, f	0.45	26.0
Junggar NW, Saur Ridge	unit 18	47.4	85.0	Late Dev.	380	23	130.9	51.1	0.89	7.9	f, cg	0.55	31.8
NTZ-Kurgasholak	unit 4.2	44.1	74.8	Early Dev.	391	12	286.5	46.4	0.81	7.8	r	0.48	27.7
Chingiz-KN&DG	unit 13.2	49.5	77.0	Early Dev.	400	8	147.7	60.2	1.05	8.0	f, r	0.72	41.1
NTZ-Karasay-KS	unit 4.2	44.8	73.9	Early Dev.	400	9	322.0	59.0	1.03	11.0	cg	0.69	39.8
Tuva	unit 38	52.0	96.0	Early Dev.	413	14	scatt	42.0	0.73	2.9		0.42	24.2
Chingiz-S2-AY	unit 13.1	48.0	80.7	Silurian	430	8	168.0	13.2	0.23	8.4	cg	0.12	6.7
Chingiz-S1	unit 13.2	48.6	78.2	Late Ord.	436	2	216.5	-2.8	-0.05	13.3	r	-0.02	-1.4
NTZ-Botmoynak	unit 4.1	42.9	71.5	Late Ord.	447	4	336.6	-11.1	-0.19	8.8		-0.10	-5.6
North-Bazarbay-BZ	unit 9	53.2	70.3	Late Ord.	453	9	298.0	-21.0	-0.37	10.0		-0.19	-10.9
North-Ishim River-IS	unit 8	52.5	66.8	Late Ord.	453	9	12.0	-24.0	-0.42	9.0		-0.22	-12.6
NTZ-Almaly	unit 4.1	42.8	71.7	Late Ord.	457	4	31.1	-17.7	-0.31	4.0	f	-0.16	-9.1
North-Saga-SG	unit 9	52.9	71.5	Mid. Ord	466	9	155.0	-19.0	-0.33	7.0	f	-0.17	-9.8
Chingiz-OV-OS	unit 13.2	48.6	78.9	Mid. Ord	480	3	146.3	-23.1	-0.40	14.8	inc-f	-0.21	-12.0
Bateny Block, Karasuk Fm	unit 27	54.3	90.7	Late Camb.	507	15	131.8	-29.2	-0.51	18.6	r, f	-0.27	-15.6
Bya-Katun block, Ust-Sema	unit 25	51.6	85.9	Late Camb.	507	18	138.8	-22.1	-0.39	6.9		-0.20	-11.5
Chingiz-CU	unit 13.2	48.7	79.0	Late Camb.	515	3	109.1	-35.2	-0.61	9.8	f	-0.34	-19.4
Bateny Block, poles 14-16	unit 27	54.3	89.5	Early Camb.	528	16	7.2	-13.4	-0.23	11.2	f	-0.12	-6.8
Bya-Katun block, Manzherok	unit24	51.6	85.5	Early Camb.	528	17	101.6	-28.8	-0.50	9.7	r, f	-0.27	-15.4

References: (1) Levashova et al., 2003a; (2) Levashova et al., 2003b; (3) Collins et al., 2003; (4) Bazhenov et al., 2003;
(5) Van der Voo et al., 2006; (6) Levashova et al., 2006; (7) Bazhenov et al., 2007; (8) Levashova et al., 2009; (9) Bazhenov et al., 2012;
(10) Bazhenov et al., 2013; (11) Bazhenov et al., 2014; (12) Abrajevitch et al., 2007; (13) Abrajevitch et al., 2008;
(14) Bachtadse ety al., 2000; (15) Metelkin et al., 2000; (16) Merkulov et al., 2004; (17) Kazansky et al., 1996; (18) Kazansky et al., 1998;
(19) Nie et al., 1993; (20) Audibert and Bazhenov, 1992; (21) Sharps et al., 1992; (22) Wang et al., 2007; (23) Didenko and Morozov, 1999;
(24) Kovalenko, 2010; (25) Huang et al., 2001; (26) Pisarevsky et al., 2006; (27) 27 Bazhenov et al., 1993; (28) Metelkin et al., 2013;
(29) Kravchinsky et al., 2002; (30) Xu et al., 1997; (31) Alexyutin et al., 2005.

Table 1: Table summarising the palaeomagnetic observations used in this paper which were published in the following articles: Merkulov (1982), Audibert and Bazhenov (1992), Bazhenov et al. (1993, 2003, 2008, 2012, 2013, 2014), Nie et al. (1993), Kazansky et al. (1996, 1998), Xu et al. (1997), Didenko and Morozov (1999), Bachtadse et al. (2000), Metelkin et al. (2000, 2013), Huang et al. (2001), Kravchinsky et al. (2002), Collins et al. (2003), Levashova et al. (2003a, b, 2007, 2009), Alexyutin et al. (2005), Pisarevsky et al. (2006), Van der Voo et al. (2006), Abrajevitch et al. (2007, 2008), Wang et al. (2007), Kovalenko (2010). Our survey included a much larger number of published observations, many of which had to be discarded for such reasons as insufficient documentation of the observation (some of such papers were written by people we know to have done excellent work in the past and whose insufficiently documented observations we excluded actually agreed with our results), imprecise age dates, imprecise ages of magnetisation, possible and definite remagnetisations. We also did not include in this table any observations on Precambrian and post-Altaid magnetisations.

of the palaeomagnetic data.

In a few cases before the late Permian we allowed a 5° latitudinal error for the observations in our databank. In the late Permian one observation showed such flagrant contradiction with well-established geology that we discarded it. To honour exactly the declination data we frequently had to distort some of the Altaid units, although the observed declinations may have resulted from internal strike-slip movement without really requiring distortion of the entire unit. The reason why we opted for distortion is that it more obviously shows the choice requiring more deformation than otherwise. This will lead to easier tests in the future of the appropriateness of the choices we made. Only in the late Permian the declination data are such that they obviously point to internal deformation of units along shear zones, although such zones were not reported in our palaeomagnetic observation sources. One important realisation during the reconstructions was that *detailed* structural data are always needed from a fairly large area around palaeomagnetic observation points for them to be evaluated properly. The absence of such data will always leave the interpretations ambiguous.

For the units from which no palaeomagnetic observations are available, geology alone guided the reconstruction. For this we first estimated, on the basis of regional structure and stratigraphy, and course of surmised evolution, where the unit would fit as was done by Şengör et al. (1993) and Şengör and Natal'in (1996). Then we checked about it whether the position we chose was in harmony with the surrounding units and whether this position satisfied the relative position of any given unit with respect to those from which palaeomagnetic data are available and with the previous and the next reconstructions. This method was critically dependent on choosing an initial plate tectonic model that guided our estimation of what the evolutionary course of the individual units would be. We followed Şengör et al. (1993) and Şengör and Natal'in (1996) in choosing initially a subduction-accretion model *along two arc fronts for the entire Altaid System* with no collisions of discrete continental objects or island arcs! The evolution of magmatic fronts as reported in these earlier papers and corroborated by the new isotopic age data as reported in Part I (Şengör et al., 2014) dictated this choice. The reason is illustrated in Fig. 2.

In this figure, A shows a continuous arc with four emergent segments plus another arc ramming the previous one in the middle (as in the present-day world the Izu-Bonin Arc ramming the Honshu emergent segment of the Japanese Arc at the Fossa Magna) creating a double syntaxis (s). Between the emergent segments of the continuous arc, the trench trace defines two deflections (d), because of the weaker development of the arc massif (the submerged segments). In this configuration we have two magmatic fronts: a continuous one characterising the main arc and a shorter one on the ramming arc. All arc segments show synchronous arc activity, at least in theory. In Part I we pointed out (see especially Fig. 9 there) that for an arc to display lateral continuity of magmatic activity, in some cases it may be necessary to take an interval as long as the entire Cainozoic into account, but for most cases this is not true.

In Fig. 2B four buoyant objects are seen behind a subduction zone: two are above it and contain magmatic arcs and two are so far away that they show no subduction-related magmatism. This is one typical 'terrane' scenario. The continuity of magmatic fronts in the Altaids excludes such a scenario.

Fig. 2C shows four active arc segments connected by transform faults. The only place where such a scenario is seen in the present-day world is in the Caribbean Arc and the Southern Antilles where *only one arc segment* has gone through a continental opening. Such a geometry is seen nowhere else and would be dynamically difficult to produce because it would be difficult to slice up a major plate unless seriously stressed. That it is seen nowhere on earth today as depicted in Fig. 1C corroborates ist impracticability.

Fig. 2D is another 'terrane' scenario where four parallel subduction zones exist. Again, the present-day earth shows no such geometry of parallel subduction zones all simultaneously active. This seems to be a favourite one among the critics of the Şengör et al. (1993) and Şengör and Natal'in (1996) mo-

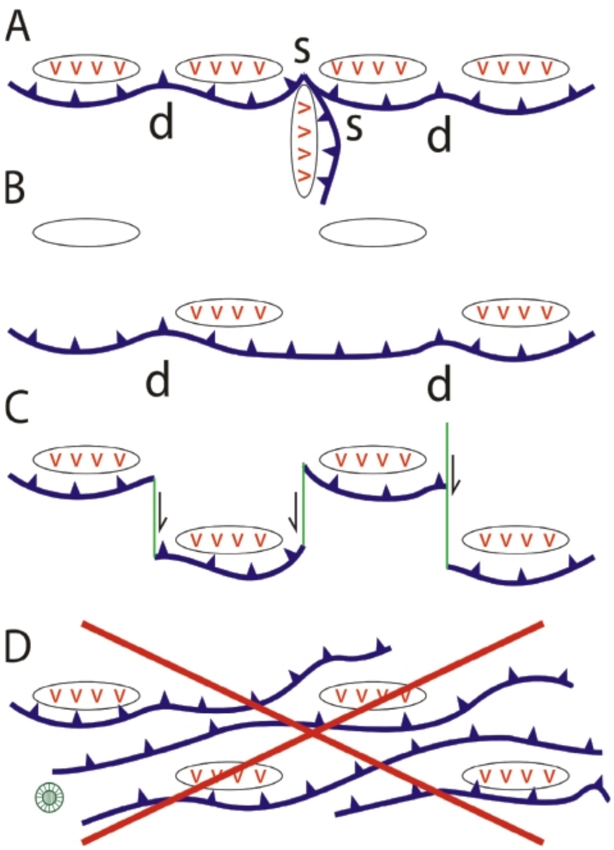

Figure 2: Four sketch maps showing four possible arc geometries. The first one (A) is what is seen in the Altaids. The second (B) and the fourth (D) illustrate two possible independent 'terrane' interpretations. Both are inapplicable to the Altaids and D is inapplicable on this planet, because major subduction zones do not crowd in the way shown. C is one example of a segmented arc which does not occur on earth unless a major subduction zone is forced to go through a hole between two major continental pieces, such as that of the Caribbean or the Southern Antilles.

del, but the present-day earth does not support such a model. In the Tethyan realm such a geometry did exist during the medial Mesozoic, but with at most two subparallel subduction zones. That geometry existed only during the Jurassic once and only in Tibet and during the Cretaceous again in Tibet and in a short segment of the Mediterranean Alpides in Turkey, i.e. for brief times and short distances. Such a model would be difficult to envisage for the immense Altaid System.

The continuity of the magmatic fronts thus forces us to assume a single arc geometry (actually two arcs as the Tuva-Mongol fragment had two subduction zones on is both sides). Once this choice is made, we know what to look for in each unit: we identify the backstops and the arc massifs. The next question concerns the arc facing and what sort of an arc we had before us i. e., ensimatic or ensialic. The internal stratigraphy decides that. The stratigraphy of each arc segment and its structural evolution, supplemented by the petrology and the ages of the coeval igneous rocks are matched with possible 'provenance' or 'mother' cratons. We thus fitted the arc segments onto their mother cratons. At this stage a simple independent check is the geometric compatibility of the fitted pieces with the margins onto which we try to fit them: an ensialic arc postulated to have rifted off a continent, for instance, could not have been much longer than the margin on which it had supposedly originally formed. Tectonic environments further guide us. Some such examples have been documented and discussed in Şengör and Natal'in (2004).

Once the arcs are placed in their original positions, the next question is naturally how the units evolved and moved. Here, the magmatic fronts and the age spans of subduction-accretion complexes is of decisive help. Magmatic fronts for a given age ('age length' is taken at most 50±10 Ma: see Şengör et al., 1993, 1994, 2014) are carefully mapped from the existing geological maps and can now be checked against the isotopic age data provided in Part I (Şengör et al., 2014). Cessation of subduction-accretion complex growth is commonly seen to have been brought about by the strike-slip emplacement of a different unit in front as seen by a variety of geological indicators such as intervening shear zones with folds having steeply plunging hinges and horizontal lineations on steep foliation planes, common cover sequences, stitching plutons and/or doubling of a given magmatic front.

In the following we present briefly the evolution of the Altaids between the Ediacaran and the late Jurassic using Figures 3-17 as a basis. For text we closely follow Şengör and Natal'in (1996), in many places just copying it, with a view to showing how little the interpretations had to be modified in view of newer data, despite the numerous claims in the subsequent literature to the contrary. None of these claims have offered alternative reconstructions using the newer data, thus weakening their substance. The account below shows most of them to be unjustified.

4. Geological evolution of the Altaids

Any statement without a reference below is based on Şengör and Natal'in (1996). We do not repeat the references given there to save space.

4.1 Pre-Ediacaran prologue

Mesoproterozoic (ca. 1.6 to 1.0 Ga) events in the Russian and very especially in the Siberian cratons are of importance for the understanding of the early stages of the Altaid evolution, although they were not parts of that evolution. The Mesoproterozoic rifting, which was the first event at the beginning of the deposition of the cover of the Siberian Craton at about 1.6 Ga, formed the initial layout of the Vilyuy Aulacogen separating the eastern half of the craton into two parts together with the Urin Aulacogen in a NE direction as well as smaller extensional structures distributed along craton periphery (Parfenov and Kuzmin, 2001). The same rifting is also believed to have caused the rifting of a continental fragment now formed from the Barguzin, Derba and the Sangilen (37[1]) microcontinental pieces (Fig. 1), as judged from the agreement of the sequence of their sedimentary cover with that of the Siberian Craton (Berzin and Dobretsov, 1994). This continental fragment collided back with the passive margin of the Siberian Craton in the Patomskoe Nagor'ye[2] along the Muya suture (between the Barguzin and the Patom in Fig. 1) during the Baykalide orogeny in the late Riphaean (Zonenshain et al., 1990; Berzin and Dobretsov, 1994). The suture is covered unconformably by Vendian rocks. Farther to the northwest (Vendian geographical orientation!) the Sangilen fragment (37) collided with the Darkhat Unit (36) forming then a part of the active continental margin of the Tuva-Mongol Unit (43). Farther to the southeast, in the Yenisey Kryazh[3] (Figs. 6 and 18), the passive continental margin of the Siberian Craton was transformed into an active margin at 800 Ma, after the collision of the Central Siberian Arc with the Craton (Vernikovsky et al., 2003a, 2004, 2009). The collisional event was followed by the formation of the east-facing Isakovskaya Island Arcs (700–630 Ma) along the western margin of Siberia (immediately to the west of the suture forming the western boundary of the Yenisey Kryazh in Fig. 1, south of the intersection of the 61°N and 90°E and north of the intersection of 55° N and 94° N). This arc was thrust onto an ophiolite (700–630 Ma) and Ediacaran (Vendian) molasse. Almost simultaneously with the thrusting, alkaline basaltoids, trachytes, syenites, and A-type granites herald a new rifting event in the Yenisey Kryazh (Vernikovsky and Vernikovskaya, 2006), which, besides petrological data, is supported by structural and sedimentological observations (Sovetov et al., 2007). Rifting can also be inferred from presence of trachybasalts, basalts and rhyolites (bimodal series) in Central Taymyr (Vernikovsky et al., 2009) where rhyolites yield U-Pb age of 600 Ma (Pease and Vernikovsky, 2000).

[1] Numbers in parentheses in this section refer to tectonic units displayed in Fig. 1.
[2] I. e., the Patom Highland.
[3] I.e., the Yenisey Crags.

The Mesoproterozoic rifting may have led to the isolation of the Tuva-Mongol Unit (43.1), although geological evidence for this event largely has been obliterated subsequently by the convergent events between the Tuva-Mongol Unit and the Siberian Craton. On the basis of palaeomagnetic observations, Kravchinsky et al. (2001, 2010) suggest a close proximity of the Siberian Craton and the Tuva-Mongol Massif during Ediacaran–Early Cambrian time. The Tuva-Mongol Unit, essentially a continental arc massif, is a large "isoclinal," almost "ptygmatic" orocline with the highly disrupted late Proterozoic to Triassic Khangai-Khantei Accretionary Complex (unit 43.2) in its core. In the literature following Şengör and Natal'in (1996) there were frequent complaints that they had assumed everything in the Altaids to be juvenile (Kröner et al., 2007, 2008, 2014; Rojas-Agramonte et al., 2011), yet there is here a large Precambrian continental core. This complaint is based clearly on not having read at all what had been written by Şengör et al. (1993) and Şengör and Natal'in (1996) and the many derivative papers they published. Since these criticisms do not target a real problem we simply ignore them.

A part of the Khangai-Khantei Accretionary Complex (43.2) was extruded east and northeastward during the early and medial Mesozoic while the Tuva-Mongol 'pincher' was closing (Şengör and Natal'in, 1996; Van der Voo et al., 1999 and in press) and went to the east to form the eastern part of the Mongol-Okhotsk belt as far as the southeastern corner of the Okhotsk Sea shelf. The Khangai-Khantei Accretionary Complex is pinched out completely in easternmost Mongolia and Russia such that the limbs of the orocline consisting of the pre-Altaid, i.e., Precambrian, continental crust are opposed directly against each other (Figs. 2 and 17). In the Stanovoy region, the northern limb, now separated from the Siberian Craton by a large dextral strike-slip fault zone (Stanovoy Fault) of Mesozoic age (Fig. 1: Natal'in et al., 1985), consists of the same Precambrian rock assemblages and similar structures as the Aldan Shield of the Siberian Craton (Kozlovsky, 1988). The similarity of these rocks and structures may indicate that initially the Siberian Craton and the Tuva-Mongol Massif formed parts of one continent (Şengör and Natal'in, 1996; Kuzmichev et al., 2001; Yakubchuk, 2004; Wilhem et al., 2012). Pre-Ediacaran bimodal volcanic rocks of the unit 36 and in the western part of Tuva-Mongol Massif are interpreted as evidence of rifting along the massif margins (Kovalenko et al., 2004), although some prefer to interpret these rocks as subduction-related (Tomurtogoo and Bayasgalan, 2002; Badarch et al., 2002) considering their age Cryogenian-Tonian. This age determination is more commonly used within the framework of ideas about rifting because it is related by the authors using it in this context to the Rodinia breakup. We do not make that association. The rifting and subduction interpretations need not be mutually exclusive as rifting above a subduction zone in this setting seems entirely possible. Together with the rift-related Neoproterozoic rock assemblages at the western margin of the Siberian Craton, these data indicate the presence of a narrow sliver of Precambrian continental crust that had partly rifted from the Siberian Craton in the Neoproterozoic then rotated counterclockwise while its eastern end remaining attached to the craton in the Stanovoy region (Kuzmichev et al., 2001; Yakubchuk, 2004; Wilhem et al., 2012). Nevertheless, how this occurred kinematically is now not clear, but it seems that the southern part of the Tuva-Mongol Arc Massif actually rifted from the present western margin of the Siberian Craton essentially opening the ocean the later closure of which later led to the construction of the Baykalides. The geometry of the Tuva-Mongol Massif in the Ediacaran (Fig. 3a) implies a minimum of 90° anti-clockwise rotation although as of now we are not familiar with any data to substantiate that. The Neoproterozoic rift-related volcanics of the Tuva-Mongol Arc Massif crop out together with calc-alkalic volcanics which are probably subduction-related as one can surmise from their geochemistry. Neoproterozoic ophiolites and sedimentary rocks in the unit 36 (Tumurtogoo and Bayasgalan, 2002; Sklyarov et al., 1996; Kuzmichev et al., 2001, 2005) appear to be parts of an accretionary complex. Both rock assemblages are located along the side of the Tuva-Mongol Arc Massif, which, during the rotation, was facing the Siberian Craton, implying an active margin on the face receding from the Siberian Craton during the rotation implying a plate boundary geometry, more complicated than is expected simply from the rotation itself.

There was also subduction along what later became the inner margin of the Tuva-Mongol Orocline at the same time. Although not well-constrained by any geochronological or palaeontological data, Mesoproterozoic ophiolites had been assumed (Tumurtoogo, 1989) in the Khangai-Khantey Unit. Recent studies have revealed the presence of only Neoproterozoic rocks as the oldest members in the Khangai-Khantey Unit (Kovach et al., 2005; Jian et al., 2010).

4.2 Ediacaran (635–541 Ma; Figs. 3A and B)

The Neoproterozoic history of the western margin of the Siberian Craton is similar to that of the eastern margin of the Russian craton, along both of which originated later the Urbaykalide Orogenic System formed from the Pre-Uralides and the Baykalides (see below). The structures of Yenisey Kryazh continue to the Taymyr Peninsula and turn around the Kara Block to join the Pre-Uralides (e.g. Natal'in, 2011; Natal'in et al., 2012). The most important initial constraint of the Altaid evolution is the assumption that the Siberian and the Russian cratons had been united as a single cratonic mass along their present northern margins, like a pair of Siamese twins connected head-to-head during the earliest Ediacaran and that they parted company sometime later during the early Ediacaran, towards 600 Ma. Evidence for this was presented in Şengör and Natal'in (1996) and, contrary to numerous later claims, there are no palaeomagnetic data to disprove this assumption. An alkalic complex in northern Timan consisting of gabbros, syenites, and granites intruding probable Neoproterozoic turbidites in a trough was recently dated at 613-617 Ma by zircon ion microprobe dating. Timanian Orogeny followed this rifting at about the 610 to 560 Ma interval (Larionov

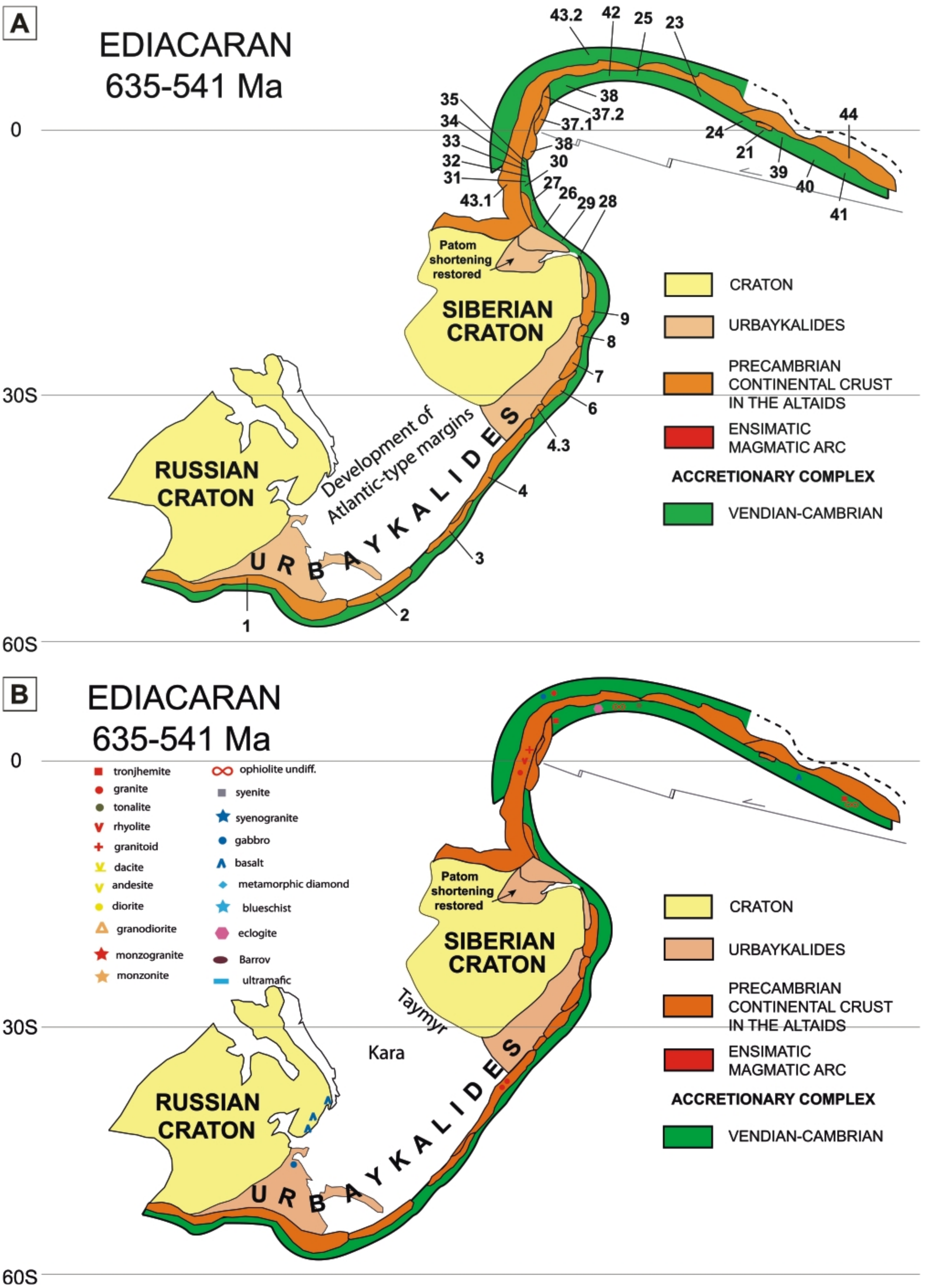

Figure 3: A. A possible Ediacaran reconstruction of the Altaids. The heaviest line bounding accretionary complexes indicate position of subduction trenches. We did not use the usual toothed depiction for subduction zone so as to leave the figure as legible as possible. B. Sketch map showing the distribution of igneous and metamorphic rocks of Ediacaran age listed in Table I of the first part of this paper (Şengör et al., 2014).

et al., 2004). Available palaeomagnetic data allow placing the two cratons as shown in Fig. 3A. Medial Ediacaran rifting between the Russian and the Siberian cratons is indicated on the European margin further by the ~600 Ma dykes in both Finnmark (Beckinsale et al., 1975) and the northern Kola Peninsula (Lybutsov et al., 1991) just as in northern Siberia in northern Taimyr (Vernikovsky et al., 2004) and extensive Ediacaran diamictite and turbidite deposition and intrusions and volcanism in tectonically active basins. In the Timanides, volcanic and sedimentary rocks, granitoids, ultramafic rocks, and blueschist were accreted to the Russian Craton in latest Ediacaran to earliest Cambrian time (Zonenshain et al., 1990; Olovyanishnikov, 1998; Gee et al., 2006). The accreted units are interpreted as a Neoproterozoic magmatic arc that was attached to a continental block – the Kara Block (Metelkin et al., 2005) or to an 'Arctida Continent' (Zonenshain et al., 1990; Kuznetsov et al., 2010). The Timanide orogeny occurred between 500–550 Ma and caused intrusions of 550–560 Ma (Roberts and Olovyanishnikov, 2004) and younger 510 Ma granites (Kuznetsov et al., 2010). For further details on the Timan/Pechora region, see Khain (1985), Zonenshain et al. (1990), Gustavson Associates, Inc. (1992), Lindquist (1999), Fossum et al. (2001), and Gee (2005).

Along the northern side of Kola and Kanin peninsulas an alkalic complex consisting of gabbros, syenites, and granites intruding probable Neoproterozoic turbidites are dated at 613-617 Ma by zircon ion microprobe dating. Farther east and southeast this rifting preceding the Timanian Orogeny is dated within the 610 to 560 Ma interval (Roberts and Siedlecka, 2002; Larionov et al., 2004; Roberts and Olovyanishnikov, 2004; Kuznetsov et al., 2010). Along the Uralian margin, the continuation of these extensional structures is unclear because of strong reworking by late Palaeozoic shortening and significant orogen-parallel dextral strike-slip faulting (Hetzel and Glodny, 2002; Friberg et al., 2002). However, in the polar Urals, the Vendian sequences include glacial and glacio-marine (?) deposits and mafic volcanics as well as Upper Cambrian coarse-grained clastics of presumably extensional tectonic setting, which preceded the main rifting events that created the Uralide Ocean in the Tremadocian-Arenigian (Koroteev et al., 1997). Farther south along the Uralian Orogen, the Bashkir uplifts consist predominantly of sedimentary rocks (Maslov, 2004) among which rare horizons of alkali and sub-alkali basaltic lavas are exposed (Karpukhina et al., 1999; Sazonova et al., 2010). The Neoproterozoic complexes of the Uraltau uplift is represented by metamorphosed volcanic, volcanic-sedimentary rocks, granites and ultramafic rocks (Lennykh et al., 1995; Hetzel, 1999; Leech and Willingshofer, 2004). They are exposed to the east of the Ordovician Uralian Ocean and are unrelated to the Russian Craton (Kuzmichev et al., 2001). Thus the most likely explanation of the relations is that they belong to the Timanides that were transported from the north by dextral strike-slip. They are the remnants of repeated rifting events first in the Neoproterozoic, then in the early Ediacaran–early Cambrian (Kipchak Arc), and finally in the Ordovician.

The combined Russian/Siberian continent had what appears to have been a Pacific-type continental margin of the Andean or perhaps Sumatran variety along its eastern side (Ediacaran geographical orientation) underlain by the Mesoproterozoic Pre-Uralide (=Timanide: Gee and Pease, 2004a, b; Bogolepova and Gee, 2004) collisional orogen to the east of the Russian Craton and by the Baykalide collisional orogen to the east and north of the Siberian Craton (see Fig. 3b for Ediacaran rocks isotopically dated since Şengör and Natal'in, 1996 was published). These two orogens are here interpreted as parts of a single, continuous collisional mountain belt (also see Vernikovsky et al., 2004). We hope to provide a more detailed jusitification of this interpretation elsewhere, showing the independent nature of the Pre-Uralide and the Baykalide orogens from the Uralides and the Altaids respectively: for the united single orogen we here propose the name Urbaykalides. Our judgement about the nature of the Urbaykalides has been formed on the basis of the information provided in the following publications, listed according to regions we considered, in addition to the few mentioned above: *Timan-Pechora regions in general*: Khain (1985), Zonenshain et al. (1990), Gustavson Associates, Inc. (1992), Lindquist (1999), Fossum et al. (2001), Gee (2005); *Polar Urals to Patomskoe Nagor'ye*: Vernikovsky et al. (2004); *Varanger Peninsula*: Siedlecka (1975), Hambrey (1988), Roberts and Olovyanishnikov (2004), Siedlecka et al. (2004); *Kildin Island*: Siedlecka (1975); Rybachi and Sredniy peninsulas: Emelyanov et al. (1971), Siedlecka (1975), Hambrey (1988), Siedlecka et al. (2004); *Kanin Peninsula*: Siedlecka (1975), Churkin et al. (1981), Khain (1985), Mitrofanov and Kozakov (1993), Lorenz et al. (2004), Maslov (2004), Roberts et al. (2004); *northern Timan*: Siedlecka (1975), Mitrofanov and Kozakov (1993), Bogolopeva and Gee (2004), Larionov et al. (2004), Roberts et al. (2004), Siedlecka et al. (2004); *Mezen Basin*: Grazhdankin (2004); *Pechora-Izhma Depression*: Khain (1985), Bogolopeva and Gee (2004), Maslov (2004), Pease et al. (2004); *Kolva Swell*: Swirydczuk et al. (2003), Pease et al. (2004); *Khoreyver Depression*: Khain (1985), Fossum et al. (2001), Maslov (2004), Pease et al. (2004); *Polar and Subpolar Urals*: Hambrey (1988), Bogolopeva and Gee (2004), Maslov (2004); Glasmacher et al. (2004); *Novaya Zemlya*: Drachev et al. (2010), Pease and Scott (2009); Kara Sea: Ivanova et al. (2011), Metelkin et al. (2005); *Taimyr*: Inger et al. (1999), Pease et al. (2001), Pease (2011), Torsvik and Andersen (2002), Vernikovsky et al. (2003a and 2004), Vernikovsky and Vernikovskaya (2001 and 2006), *Yenisey Kryazh*: Smit et al. (2000), Vernikovsky et al. (2003a, 2003b, 2004, 2007, 2009), Khomentovsky (2007), Kochnev et al. (2007), Nozhkin et al. (2007), Sovetov et al. (2007), Kuzmichev et al. (2008), Kontorovich (2011).

During the Ediacaran, segments of the Urbaykalide orogenic belt began to disintegrate by extension along the eastern margin of the combined Russian/Siberian continent (Fig. 3). Active rifting is documented in units 1, 3, 4, 6, 7, and 8 of the Altaid collage. Seismic profiling revealed a system of Riphaean to Palaeozoic rifts including the Vendian sediments at the western (present geographical orientation) margin of the Siberian Craton beneath the West Siberian Basin (Vernikovsky et al., 2009). The same is true in the northern unit of the Taimyr Peninsula (Vernikovsky et al., 2004). Rifting became younger southward (in the Ediacaran orientation): in the Polar Ural (i.e., Russian Craton) side, rift sedimentary rocks are of late Cambrian to early Ordovician age which becomes entirely early Ordovician in the Sakmara allochthon farther south (in addition to the references cited in Şengör and Natal'in, 1996, see Puchkov, 2002, especially fig. 2, for the entire Urals; Glodny et al., 2005, date the rifting on the Russian Craton side at about 490 Ma using zircons from metagranites).

Evidence for Ediacaran rifting exists in the Kazakhstan-Tien Shan tectonic units but such evidence is generally unknown in the Altay domain. Units 1 through 9 bearing evidence of rifting are placed in Fig. 3a along the eastern margin of the combined Russian-Siberian continent displaying evidence for the same rifting. Units 28–42 consisting mainly of the Vendian-early Cambrian accretionary complexes and arc magmatism (mostly grown on the accretionary complexes) are distributed along the northern margin of the Tuva-Mongol Massif (43.1) and the South Gobi Tectonic Unit (44). Fig. 3B shows the subduction-related magmatic rocks and accreted ophiolites on top, and on both sides, of the Tuva-Mongol Massif that have been dated isotopically since Şengör and Natal'in (1996) was published.

The late Precambrian-early Cambrian rocks of the South Gobi Unit (44: shallow-marine carbonates and quartzites sitting on old continental crust as already emphasised in Şengör et al., 1993 and Şengör and Natal'in, 1996) are very similar to the rocks of the Tuva-Mongol Arc Massif; Palaeozoic rocks are also similar and therefore we assume that in the Vendian-early Carboniferous the South Gobi Unit was a direct continuation of the Tuva-Mongol Arc Massif as it is shown in the reconstruction (see Fig. 3A). The difference between the late Precambrian shallow-marine carbonates of the South Gobi Unit (the very east of the Tuva-Mongol Arc Massif) and the same rocks in its western part (around unit 37 and 36; Fig. 3A) is that the latter contain phosphorites (Marinov et al., 1973; Ilyin and Ratnikova, 1981). Phosphorite accumulation is controlled by zones of upwelling located along western sides of oceans because of Coriolis force (Parrish, 1987) which fits palaeogeography depicted in Fig. 3A. There is no geological indication to suggest that they were separate. Placing the South Gobi Unit far away from the Tuva-Mongol Arc Massif requires independent evidence. There are palaeomagnetic data showing the western part of this massif as far south as 2.7°±10.8° S latitude during the early Carboniferous (Kravchinsky et al., 2001). For this unit to reach its early Permian position to be a part of the south Mongolian collage it would have had to maintain a speed of 15 to 45 cm/a. While 15 cm is at the edge of reasonableness yet the highest known rate from the present-day earth, between the Pacific and the Nazca Plates although not well constrained, is believed to be ≤ 15 cm/a. If such a rate is accepted as reasonable for unit 44, it is still an extremely high plate velocity (DeMets et al., 2010). The highest ever measured rate of spreading we know to have occurred on our planet was some 20–22 cm/a some 20–11 Ma ago on the superfast East Pacific Rise, where the Cocos Plate is still separating from the Pacific Plate: Teagle and Wilson, 2007). 45 cm/a is in any case an absurdly high rate of motion. Whatever adjustments one can make to massage the palaeomagnetic data, they are impossible to bring into agreement with the well-established gross geology of southern Mongolia and north China. We have therefore chosen to ignore this observation until it is further corroborated by newer observations.

All tectonic units of the Altaids which are depicted in the Ediacaran reconstruction essentially consist of magmatic arcs and accretionary complexes. All of the magmatic arcs active at this time were built on pre-existing, i. e., Precambrian, almost entirely Meso- and Neoproterozoic Urbaykalide crust ripped off from the Russian and the Siberian cratons at different times. This, combined with the reconstruction of the tie points of magmatic fronts and arc massif/accretionary complex boundaries as explained in Şengör and Natal'in (1996), allow us to reconstruct a single subduction zone along the eastern margin of the combined Russian/Siberian supercontinent and another along the northern margin of the Tuva-Mongol/South Gobi arc. As Fig. 3A shows, at the beginning of the Altaid evolution, that there were two subduction zones active within what was to become the Altaid Superorogenic Complex: fragments of the Ediacaran-early Cambrian accretionary complexes in the Khangai-Khantey Unit clearly show the existence of the subduction zone also to the south of the Ediacaran Tuva-Mongol Arc Massif

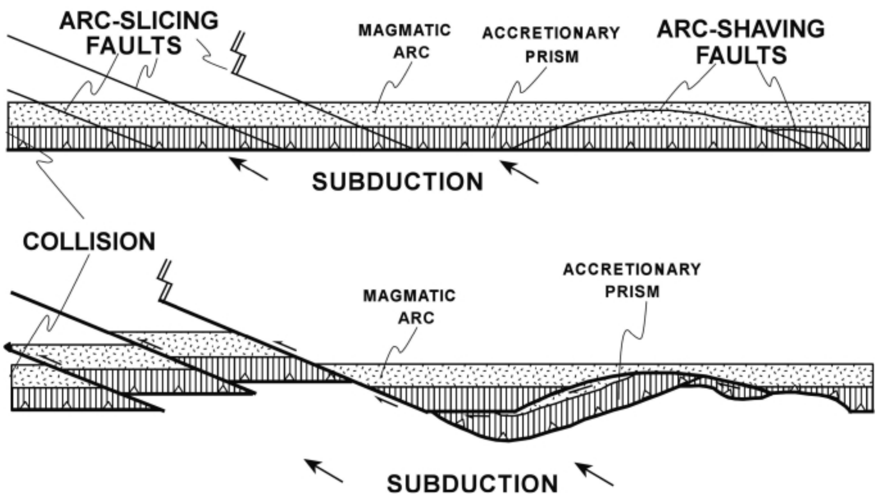

Figure 4: Sketch map showing the concept of arc shaving (to the right) and arc slicing (to the left) strike-slip faults and the tectonic consequences of their activities.

(Fig. 3A) and so do the well-dated subduction-related magmatic rocks (Fig. 3B).

The paucity of structural data does not now permit us to undo the internal deformations of the arc massif to know how wide it was at the time. It must have been at least as wide as the present-day Bougainville Island System (200 km), but more likely as the Philippines (500 km), to allow the simultaneous activity of two subduction zones dipping under it. Its present width fluctuates between 250 and 70 km and this implies that the Tuva-Mongol Arc Massif must have been shortened by some 50 to 80 % if it were as wide as the Philippines and 0% to >50% if it were as wide as the Bougainville Island System. However, the preservation of supracrustals in many places atop it makes it clear that this could not have been by folding and thrusting or homogeneous bulk shortening alone, at least not everywhere. Much arc-shaving and some arc-slicing strike-slip faulting (Fig. 4) must have elided parts of the arc massif. As we shall see in what follows, this was indeed the case.

Because of the paucity of palaeomagnetic data, we made the following assumptions to determine the geometry of the single subduction boundary along the Tuva-Mongol/South Gobi arc:

1) The analysis of the magmatic fronts and other relevant data has shown that the predominant structural style in the Altaids is strike-slip repetition of the fragments of a single arc (Şengör et al., 1993; Şengör and Natal'in, 1996, 2004). There is no direct way of determining oceanic plate geometry for times before the Jurassic. However, the coastwise motion of the tectonic units within the easterly-concave, large bend of the Tuva-Mongol Arc in a continuous anticlockwise fashion necessitates an intra-oceanic geometry something equivalent to that shown on our Fig. 3A, because the most efficient mechanism for strike-slip faulting subparallel with an arc is oblique subduction. Thus, we adjusted the overall arc geometry of the Tuva-Mongol Arc Massif to be compatible with the few palaeomagnetic observations for later times and the evolution of the assumed plate geometry in the ocean so as to be compatible with the geology.

   Generally in our reconstructions, especially of the Ediacaran and early Palaeozoic times (Figs. 3A, 6A, 7A, 8A, 10A, 11A), we assumed the presence of oceanic plates, whose cumulative size must have been something similar to the present-day Pacific Plate, which now underthrusts a subduction front for almost 20,000 km, similar to the length of the combined Kipchak and the Tuva-Mongol arcs (Fig. 5). This is compatible with the generally presumed palaeogeography of those times.

2) Structural relationships of the tectonic units in the Altay-Sayan region lead to the inference that their palinspastic reconstruction must be undertaken in the following manner: Tectonic units of the North Sayan area (units 26-30) have been assembled sometime at the transition from early to medial Cambrian. A collage in the Tannuola area (units 31-38) formed in the Silurian. Only after these two assemblies were completed, in the time span between Devonian and early Carboniferous, the units of the Salair and the Altay (units 19-25) acquired their present-day structural position. For the earliest episode of the tectonic evolution, we need to keep the northern (geographical orientation during the Ediacaran through the late Ordovician) margin of the Siberian Craton and Tuva-Mongol Arc Massif compatible with coastwise strike-slip movement. To satisfy this requirement, which is merely a postulate of our model, we undertook three further reconstructions, which unexpectedly resulted in solutions to two long-standing tectonic problems in the Trans-Baykal region:

First, the Vilyuy Aulacogen had opened during the Mesoproterozoic (Parfenov and Kuzmin, 2001) and then had closed back before the Ediacaran (Milanovsky, 1987; Zonenshain et al., 1990). Its second and main opening happend in the late Devonian. Closing back the Vilyui aulocogen is the first step in the straightening out of the arc Tuva-Mongol—North Siberian margin as far east as the hinge of the Tuva-Mongol Orocline (between units 26 and 27 in Fig. 3B).

Secondly, the collision of the Barguzin microcontinent with the Riphean Siberian passive continental margin in the Patom Highland had happened at the transition from the Tonian to the Cryogenian (Khomentovsky, 1996, 2002), although the shortening in the Patom fold-and-thrust belt probably continued until the Devonian (the Silurian, however, is unfortunately not represented in the stratigraphy of the Patom marginal fold-and-thrust belt; poorly-dated Devonian redbeds rest unconformably on the Ordovician). The reason for this deformation that is spatially restricted in the west by the Angara-Lena region of the Siberian Craton and in the east by the Zhuinsk Fault has not been clear. It has been assigned, for example, to the collision of the Barguzin Microcontinent (e.g., Zonenshain et al. 1990), but a 200 Ma duration of the foreland folding is clearly too long to regard this explanation plausible. The Zhuinsk Fault delimits the Patom fold-and-trust belt in the east and has long been known to be a right-lateral strike-slip fault. From the structural pattern shown in the geological maps of the region it seems obvious that the Patom fold-and-trust belt and Zhuinsk Strike-Slip Fault are genetically related. The main problem related to the Zhuinsk Fault kinematics has been its abrupt termination against the Tuva-Mongol Unit (see Fig. 1). There, it is cut by NW-striking Cainozoic sinistral strike-slip faults of unknown magnitude of displacement (Sherman and Levi, 1977; Balla et al., 1990). In the following paragraphs we discuss the mechanism for the formation of the Zhuinsk Fault and the Patom fold-and-trust belt but here we mention this problem just to underline the necessity of the palinspastic restoration of the Patom shortening and Zhuinsk Fault displacement for the Ediacaran reconstruction to obtain a straight edge for the northern Siberian and Tuva-Mongol margin (see Fig. 3a).

The third step to produce a straight Tuva-Mongol-North

Angara margin is to bend the Tuva-Mongol Arc Massif at the southern (present geographical orientation) end of the Zhuinsk Fault (see Fig. 3A). Taking into consideration the polyphase metamorphic and magmatic evolution in this region spanning the entire Palaeozoic, the Palaeozoic westward migration of the hinge of the Tuva-Mongol Orocline is plausible. Moreover, our palinspastic reconstruction as well as some other reconstructions have shown that the migration of the hinge of the Tuva-Mongol Orocline is unavoidable. That there is no evidence for Ediacaran magmatic arc activity in Sangilen Unit (37.1 and 37.2) and that the accretionary complex which is now in front of it has a minimum age of early Cambrian suggest that the ophiolites and other accretionary prism rocks lining the outer margin of the unit

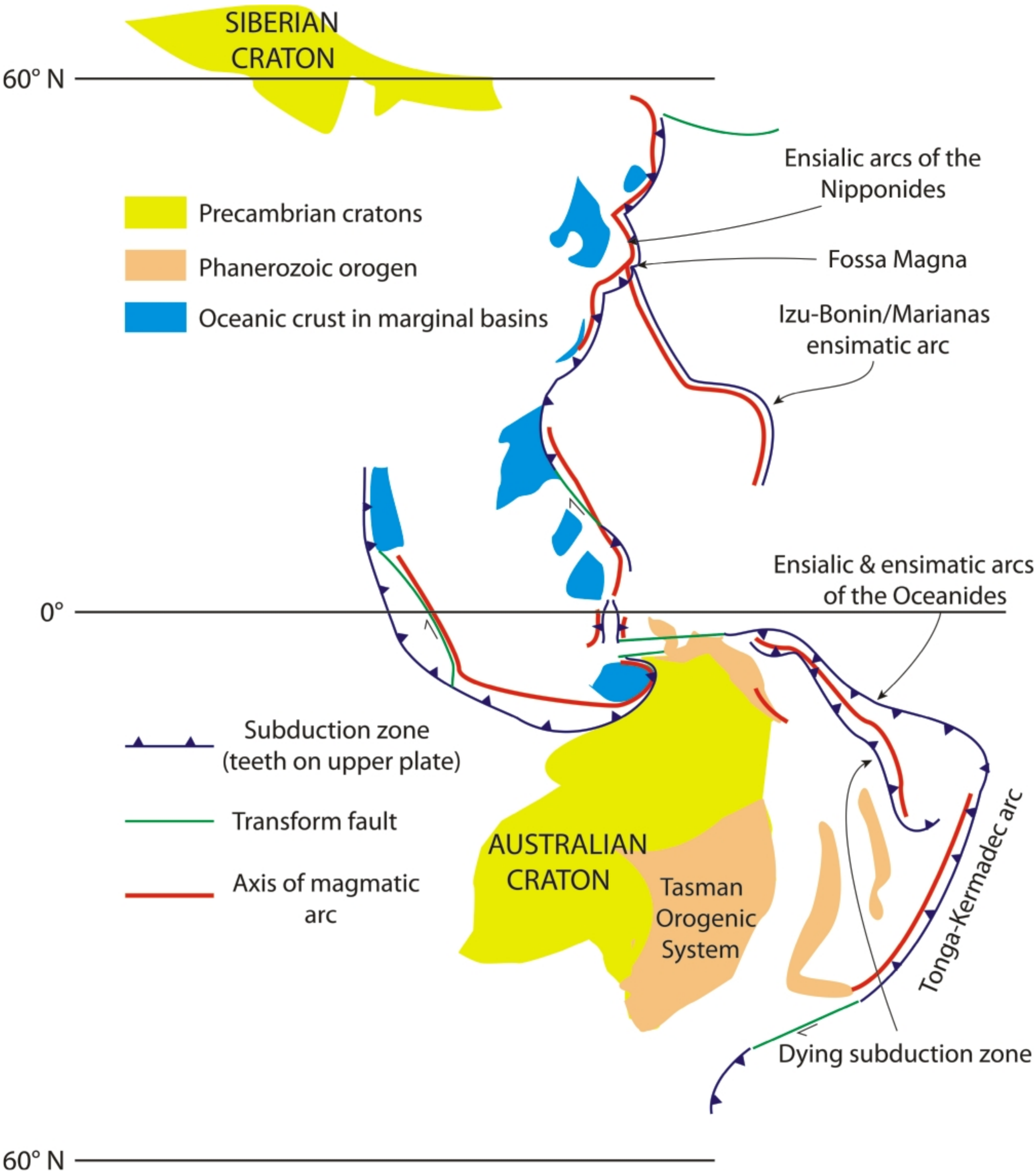

Figure 5: The arcs of the western Pacific and the northeast Indian Ocean shown to illustrate the continuity of the major subduction zones. This is the largest subduction system on earth today and shows no terranes tied to independent mini subduction zones stampeding across the Pacific Ocean. This system is the best analogue for the Kipchak and the Tuva-Mongol arcs of the Altaids. We also showed the two major ancient cratonic nuclei. Note that their sizes are not dissimilar to those of the Russian and the Siberian cratons.

now and also cropping out in its central part were brought there by the later major Altaid coastwise strike-slip transport. This supports the presence of a trench-trench transform fault (i.e. a subduction-free margin) in this inferred dog-leg segment of the Tuva-Mongol Arc before the onset of the long-shore transport. The geometry of our postulated ridge makes this possible, although the scale of our reconstructions do not allow its exhibition (Fig. 3A).

The Darkhat Unit (36) contains a Mesoproterozoic accretionary complex twice as long as the related magmatic arc (see Fig. 1). In the Ediacaran reconstruction (Fig. 3A), the magmatic arc of this unit is placed as a direct continuation of the coeval volcanics of the same type in western Mongolia (Darkhan Series) which stretch as a narrow north-south belt along the westernmost boundary (present geographical orientation) of unit 43.1. Thus the Riphaean accretionary complex "too long" for unit 36 is seen to have belonged both to unit 36 and unit 43.1, forming two segments of the same ancient magmatic arc.

The Kuznetsk-Alatau Unit (27) having a piece of the pre-Altaid (i.e. Precambrian) continental crust overlain by thick upper Proterozoic carbonates is shown as the continuation of the Barguzin microcontinent, also characterised by a thick cover of similar Neoproterozoic carbonates (Rudenko, 2009). Contrary to unit 27, these carbonates have been subjected to metamorphism up to granulite facies in the early Ordovician (488 Ma) and are cut by trondjemite yielding 477.6±2 Ma zircon ages (Salnikova et al., 1998).

The Eastern Sayan Unit (25), with a basement and carbonate cover similar to those of the Barguzin, constitutes a part of the arc massif of the Tuva-Mongol Unit (43.1). Its exact placement within it is inferred by assuming original proximity to the only place having a similar carbonate cover atop the presently defined Tuva-Mongol Unit (Middle Gobi region).

Units 13-20, 43.3, and 44.1 do not appear in the Vendian reconstruction because their formation as yet lay in the future.

4.3 Early Cambrian (541-521 Ma: Figs 6A and B)

In early Cambrian time, a narrow sliver of the continental crust consisting of units 1-9, which has been called the Kipchak Arc (Şengör et al., 1993, 1994), was completely detached from the combined Russian-Siberian continent (Fig. 6A). The disintegration of the latter into the two large continental masses (Russian and Siberian continents) already had happened. We have pointed out above that the separation of the Kipchak Arc from the Siberian Craton and from the Russian Craton in the Northern Urals was complete in late Cambrian time but in the Southern Urals this splitting was probably younger. This suggestion is based upon the evidence of latest Cambrian-Ordovician rifting in the Southern Urals mainly in the Mugodzhar. Unfortunately, the precise time of detachment of the southern end of the Kipchak Arc is unknown, but Puchkow (2002) shows the development of the clastic rift facies persisting during the Ordovician. The only reason to show in the early Cambrian reconstruction (Fig. 3A) a total separation of the Kipchak Arc in the south was to emphasise that we do not have the eastern half of the rift facies shown by Puchkov (2002). Fig. 3A is a challenge to find evidence that the other side also was still rifting during the Ordovician. To this day, unfortunately no such evidence is available. The Khanty-Mansi Ocean (Şengör et al., 1993, 1994) formed in the back of the Kipchak Arc what seems to have been a marginal basin. The only reason we have for calling it a marginal basin is because it opened by rupturing an active arc. During the opening, the arc continued its activity (Fig. 6b).

We placed a large transform fault, along which the Khanty-Mansi Basin opened and the ensimatic arcs of north-east and eastern Kazakhstan later formed. Locations of these arcs are shown in Fig. 1. The strike-slip duplication of the Northern and Southern Sangilen (units 37.1 and 37.2) indicate that oblique subduction under the Tuva-Mongol Arc had already led to right-lateral strike-slip movement of some of the southern parts of the Tuva-Mongol Arc Massif and Accretionary Complex. The timing of the right-lateral strike-slip duplication of Kuznetskii Alatau (27) and North Sayan (30) units is still poorly constrained. En-échelon pattern and rhomb-like shapes of subduction-related granitoid plutons seen in geological maps (Berzina et al., 2011) permit an inference about broad dextral shearing along the NW-striking Kuznetsk Fault. Dextral bend in the same structural frame can be also seen in a shape of the more then 100 km long but narrow intrusion of “alkali-mafic” rocks that Berzina et al (2011) explain as a rifting event. Suggesting a model of arc-parallel tectonic transport along Altay side of the Siberian Craton essentially identical to our Altaid model (Şengör et al., 1993; Şengör and Natal'in, 1996, 2004), Dobretsov (2011), Dobretsov et al. (2013a), Metelkin et al. (2011) and Metelkin (2013) imply sinistral motion of the tectonic units during the early Palaeozoic. This kinematics is not supported by structural observations or isotopic age determinations. Geological data are not equivocal about the fact that the dextral motions have started already in the early Cambrian. Indeed, Berzina’s et al. (2011) mapping also shows that dextral tectonic transport has been established in the Tannu-Ola region (unit 37 and 38) where biotite of metamorphic minerals yield Ar-Ar ages of 490-430 Ma (Vladimirov et al., 2000). That indicates prolonged deformation and imposes strong constraints on its beginning.

Judging from the present-day structural position of unit 21 containing Vendian-early Cambrian ophiolites, high-pressure schists and island arc volcanic rocks, we place it at the very western end of the Tuva-Mongol-South Gobi Arc. Probably already in the Cambrian unit 21 started to slide along the Tuva-Mongol-South Gobi Arc making place in its wake for the accumulation first of unit 20 and then of the unit 19, in which the oldest rocks are no older than the Ordovician. The weird hook shape of the eastern terminus (early Cambrian geographical orientation) of the Tuva-Mongol Massif is simply to satisfy the palaeomagnetic data. As indicated above, we have avoided

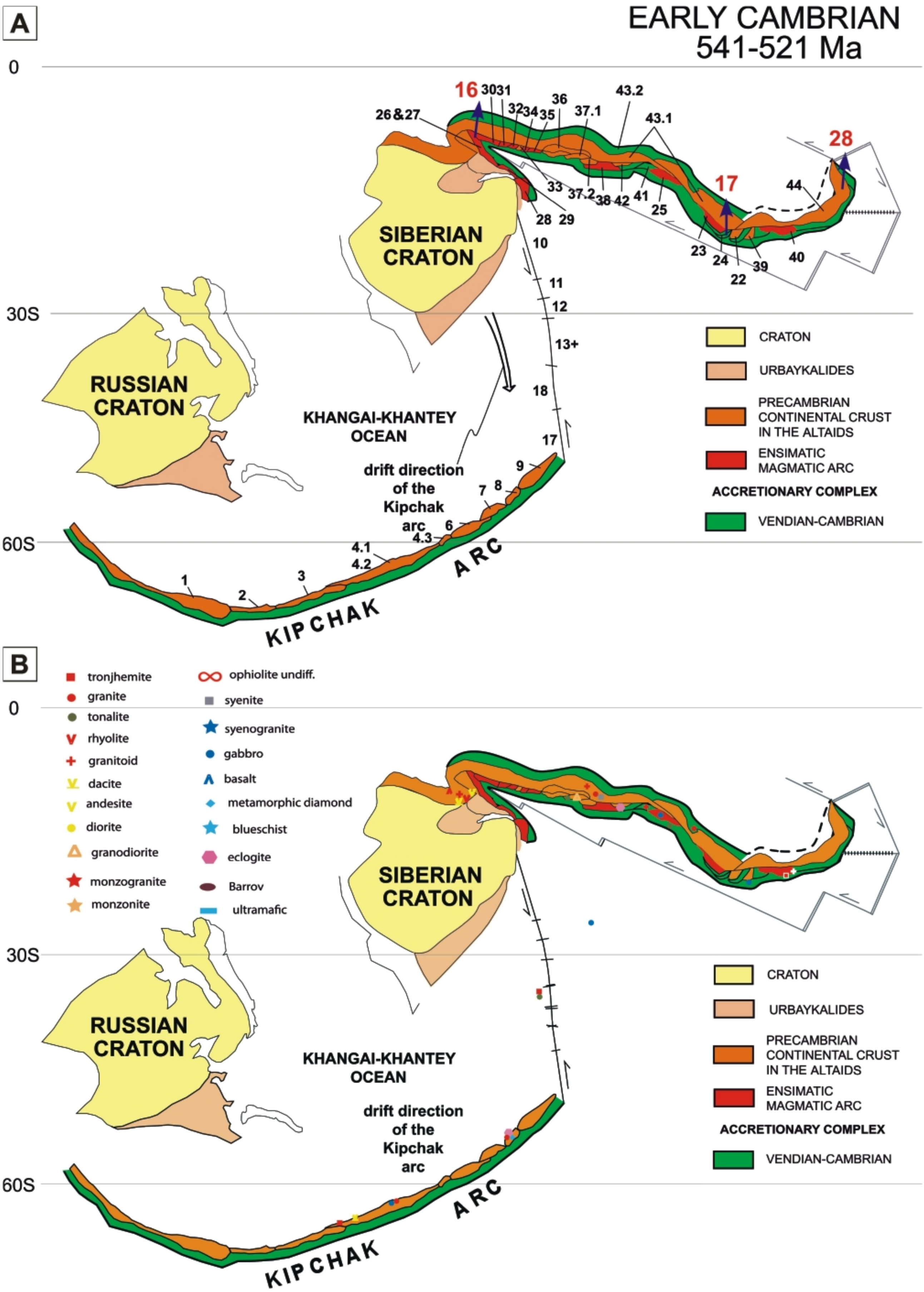

Figure 6: A. A possible early Cambrian reconstruction of the Altaids. Blue arrows indicate palaeomagnetic declination vectors with their tail at the appropriate latitude. They are keyed to Table I by the red numbers near them. B. Reconstruction showing the distribution of igneous and metamorphic rocks of early Cambrian age listed in Table I of the first part of this paper (Şengör et al., 2014).

using the uncertainty margins of the data unless made absolutely necessary by well-established and generally agreed-upon geological relationships. The hook shape and the coastwise transport along its outer side (south, east and northeast) can both be easily accommodated if an oceanic plate geometry of the kind drawn in our Fig. 6A existed. The ladder pattern indicates a zone of shortening in the ocean, the polarity of which can no longer be recovered.

The accretionary complexes belonging to the units 7 through 9 are fairly voluminous. They accumulated in front of the Kökchetav diamond-bearing terrains suggesting rapid and considerable uplift/unroofing. The resultant highlands could have fed the Kipchak trench with clastics more voluminous than in other segments of the arc.

Newly isotopically-dated magmatic arc rocks show a greater spread than the ones in the Ediacaran reconstruction. This is clearly a sampling/preservation bias, but what is most likely not such a bias is their remarkable lining up along the Kipchak and the Tuva Mongol arcs and nowhere else (Fig. 6b), because this is what the stratigraphically-dated subduction-related rocks also indicate (see Şengör and Natal'in, 1996, and Plate I).

4.4 Medial to Late Cambrian (514-485 Ma: Figs. 7A and B)

At this time, the transform fault connecting the Kipchak and Tuva-Mongol arcs had already been changed into a subduction zone above which the units 10-18 formed that are now located in norteastern and eastern Kazakhstan (Fig. 7A).

The Boshchekul-Tarbagatay Unit (13) developed as a double arc system because of marginal basin opening by splitting the arc during the medial Cambrian. In the Ordovician it was transformed into a marginal sea floored by oceanic lithosphere as inferred from the age of the ophiolites in the Maikain-Balkybek Suture separating the Boshchekul-Tarbagatay (13.1) and

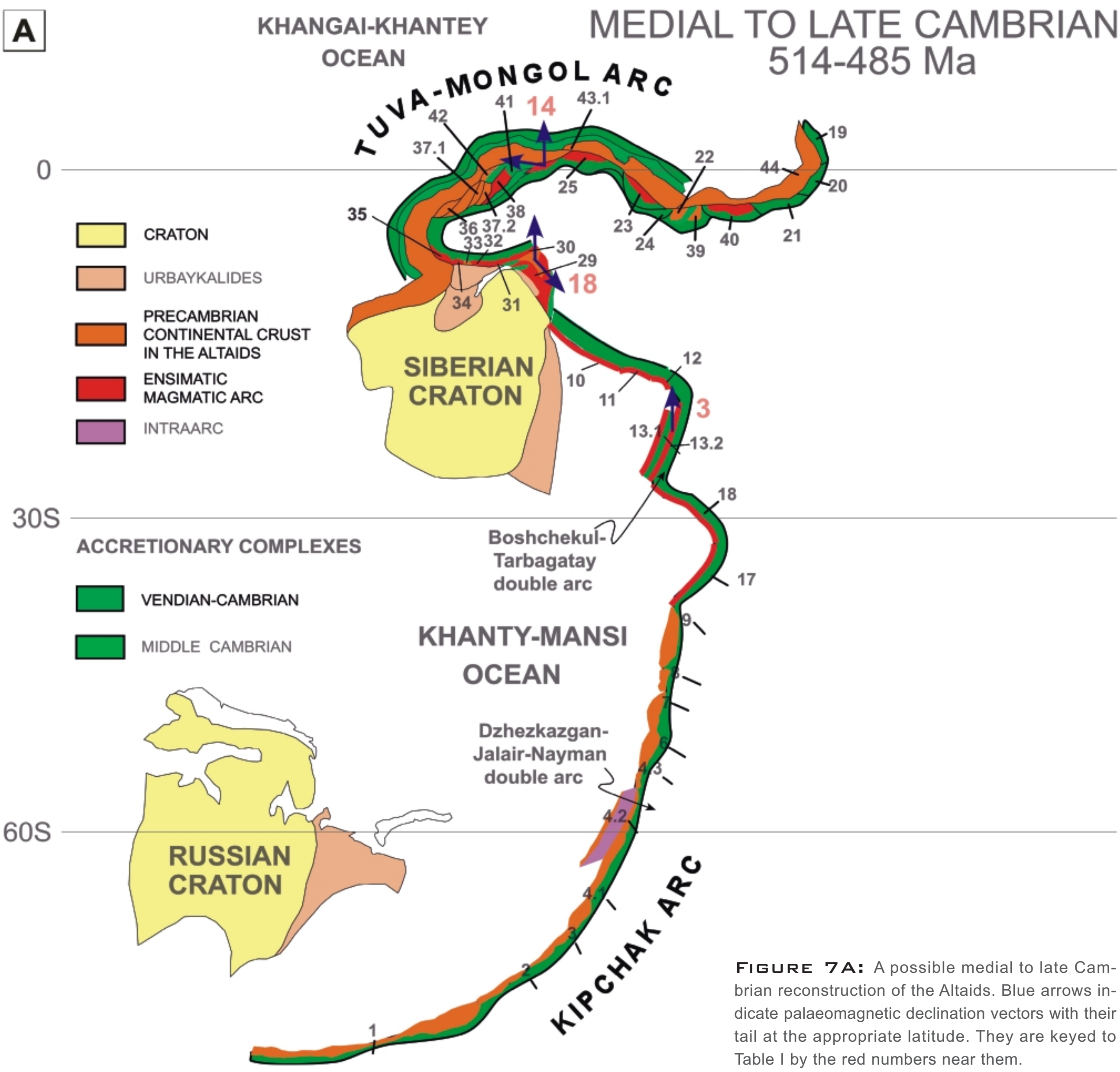

Figure 7A: A possible medial to late Cambrian reconstruction of the Altaids. Blue arrows indicate palaeomagnetic declination vectors with their tail at the appropriate latitude. They are keyed to Table I by the red numbers near them.

Bayanaul-Akbastau (13.2) ensimatic island arcs (Şengör and Natal'in, 2004). Anorther double arc system is inferred to have formed in the segment of the Kipchak Arc corresponding with the Djezkazgan-Kirgiz Unit (4.1). There, back-arc spreading caused the rifting of the Jalair-Naiman Unit which originally was a fragment of the pre-Altaid continental crust that in the Cambrian?-Ordovician turned into an island arc (see also Şengör and Natal'in, 2004).

We infer that at the end of the early Cambrian, units 26-29 and 30-35 experienced a very fast right-lateral motion with respect to the Siberian Craton and the Tuva-Mongol Unit. Units 26, 27, and 30 moved in front of units 28 and 29, accretionary complexes of which are not younger then early Cambrian. This motion accounts for the rotation of the magnetic declination measured on unit (Fig. 7A, vector ref. 17). Subduction-related volcanic activity in units 28 and 29 existed in the medial Cambrian and poorly-dated granitic magmatism lasted up to the beginning of the Ordovician, but this later phenomenon may be a result of the continuing slab descent under these units following the replacement of the subduction zone with a strike-slip fault to their east. We point out, however, that the granitic rocks have not yet been dated reliably and their age might not reach any later than the middle Cambrian. After these events the collage of the northern part of eastern Sayan (present geographical orientation) became assembled in its final shape and in the course of further evolution it was only slightly deformed. A train of arc magmatic rocks (andesites, dacites, rhyolites, and granodiorites diorites, gabbros) have been reported along the northern boundary of the Barguzin Microcontinent passing into the Tuva-Mongol Arc Massif by Gordienko et al. (2010), corroborating the existence of a subduction zone along the inner side of the Tuva-Mongol Arc Massif all the way past Lake Baykal.

Structural relationships and stratigraphy in the units of the Altay-Sayan region demand that the pimary positions of units 38 and 39 were farther to the west on the Tuva-Mongol margin than the position of units 22-25 (medial to late Cambrian geographical orientation). From these positions, units 38 and

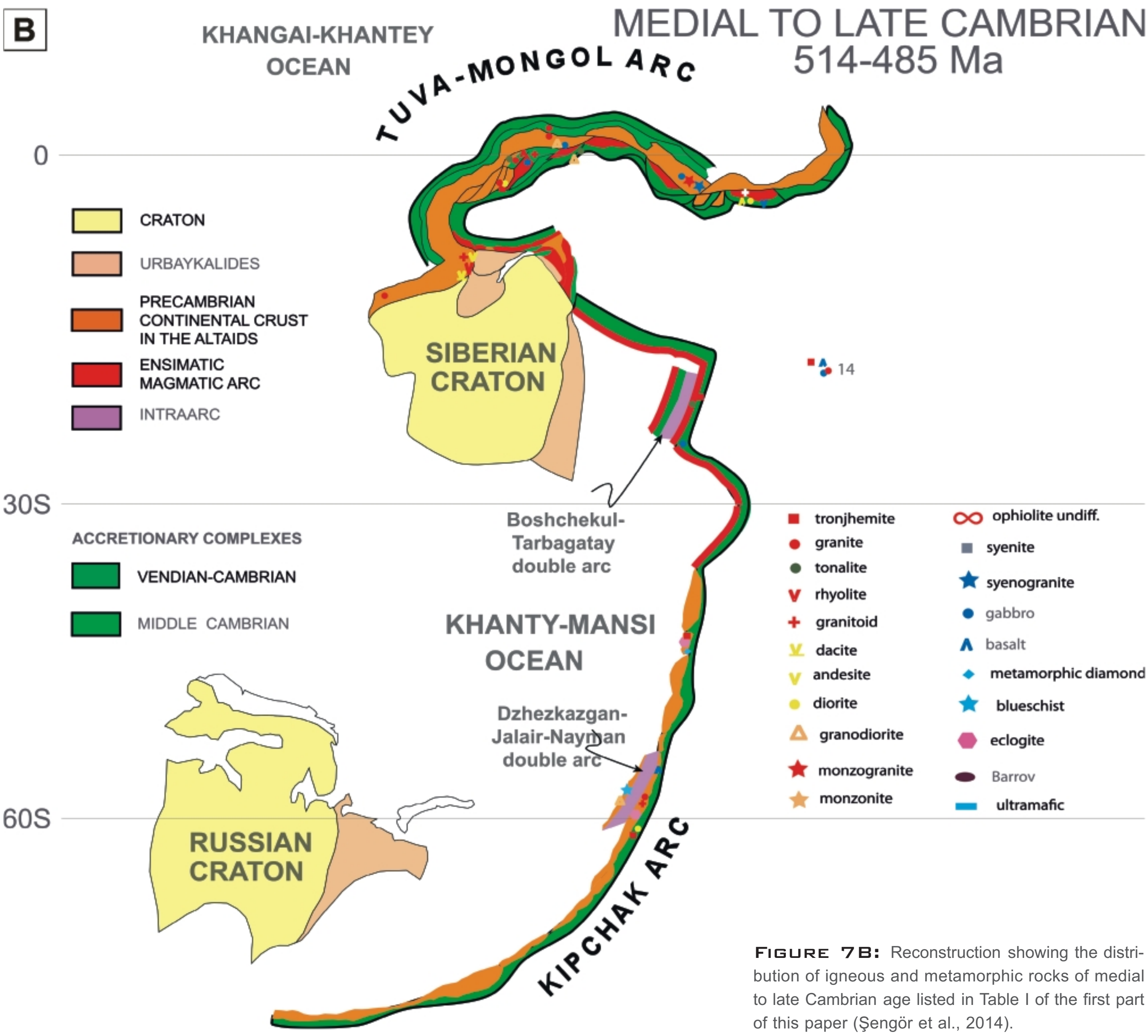

Figure 7B: Reconstruction showing the distribution of igneous and metamorphic rocks of medial to late Cambrian age listed in Table I of the first part of this paper (Şengör et al., 2014).

39 first came to the point of their final destination in the core of the West Sayan Orocline and afterwards units 22-25 overtook them and occupied the present-day frontal position. For this reason we infer that in the Cambrian units 38 and 39 moved faster than the later ones.

On unit 27 the palaeolatitude is in agreement with the reconstruction here presented, but not the declination. When one considers that while the magnetisation of unit was being acquired strong strike slip was going on in and around it, it is natural that the declination would have rotated. Regrettably we have no structural data from the precise site of the palaeomagnetic observation and therefore we have no idea how to restore the declination just as in the case of unit above.

Unit 21 continued its movement along the South Gobi Unit (44) making place in its wake for the formation of units 20 and 19.

4.5 Medial Ordovician (458 Ma: Fig. 8A and B)

At this time, the opening of the Sakmara-Magnitogorsk Marginal Sea in the Ural margin of the Russian Craton commenced (Fig. 8A). The collision, following its drift, of the Mugodzhar Arc with the southern end of the Kipchak Arc was originally postulated to be one of the main reasons for the strike-slip stacking and oroclinal bending of the Kipchak Arc (Şengör et al., 1993; Şengör and Natal'in, 1996). This is still true, but to honour the palaeomagnetic data without using their error margins, we postulated what to us seems a possible, but unlikely, scenario, thus with greater information content: since the units 13.1 and 6 plot to almost the same palaeolatitudes, we assumed that this may have been brought about by a break in the Kipchak Arc and sliding of its southern moiety left-laterally past unit 10. This results in a geometry shown in Fig. 9 originally drawn for a dextral case in Şengör (in press). In Fig. 9A an unstable TTT (trench-trench-trench) type triple junction is shown at which plates A, B and C meet. We can think of these plates as A=Khanty-Mansi Plate, B=Turkestan Ocean (I) Plate and C=Turkestan Ocean (II) Plate. As is seen Fig. 9A, this geometry would lead to a slab conflict at depth. To avoid it, the slab belonging to the Turkestan Ocean (II) must develop a gemotry equivalent to a conical fold at depth (Fig. 9B and B). The formation of such a conical fold and its lateral progression with time as required by the plate boundary evolution would be possible to check with careful map-

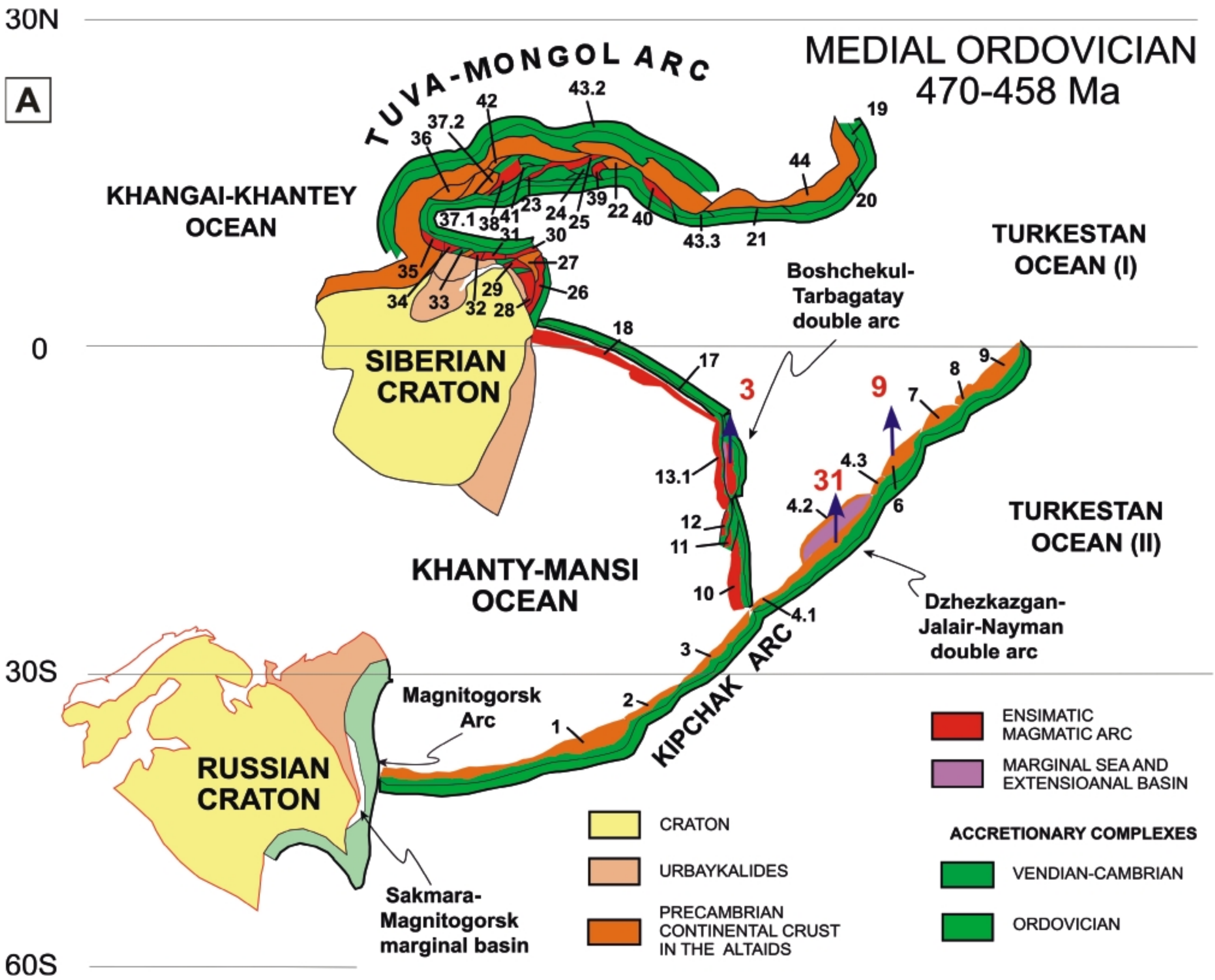

Figure 8A: A possible medial Ordovician reconstruction of the Altaids. Blue arrows indicate palaeomagnetic declination vectors with their tail at the appropriate latitude. They are keyed to Table I by the red numbers near them.

ping and dating of subducton-related igneous rocks. We offer this hypothesis and indicate how it might be tested to be able to discard it as soon as it is falsified by some simple observations that would require, however, arduous field work.

Instead of the hypothesis offered here, the Kipchak Arc may have been bent so as to bring the units 13.2 and 6 to the same palaeolatitude. Numerous palaeomagnetic observations would then have been required to check that, in our mind more likely, hypothesis. But it is better scientific practice to eliminate completely the more unlikely rival first (cf. Popper, 1994).

The time of the strike-slip stacking of the Kipchak Arc north of the postulated triple junction is inferred from the youngest ages of the rocks in the accretionary complexes of the Kipchak Units. The stacking in the Kipchak Arc by arc-slicing strike-slip faulting (cf. Fig. 4) commenced to the northeast of the Akdym Unit (12) where the youngest rocks in the accretionary complex are Middle Ordovician (Fig. 8A). Unfortunately we do not have isotopically well-dated subduction magmatic rocks here that would have offered an auxiliary check on our interpretation of the stacking.

In the Western Sayan range and in the Dzhida Valley (unit 30, 31, 33, 34, 35, and 39) the youngest rocks in the magmatic arcs and the flysch in the accretionary complexes are Ordovician-Silurian. Therefore in the medial and late Ordovician reconstructions as well as in the Silurian these units are shown in positions above subduction zones. The Darkhat Unit (36) is devoid of a Palaeozoic accretionary complex and was thus probably a part of the Tuva-Mongol Arc Massif adjacent to a fault connecting the subduction zone segments in front of units 38 and 35 (Fig. 8A). Although there are fewer observations than was the case for the medial to late Cambrian, the arc axial width of active magmatism seems to have increased during the medial Ordovician. If true, this may have been a result of strike-slip stacking and across-strike widening of the Tuva-Mongol Arc Massif.

The Salair-Kuzbas (23), Western Sayan (39), Charysh-Chuya-Barnaul (22), Kobdin (40), and Eastern Tannuola (38) units have accretionary complexes of Ordovician age and, behind them, magmatic arcs. In our palaeotectonic reconstruction they are all placed behind the subduction zone south ('outside') of the Tuva-Mongol Unit (Fig. 8A). Units with older accretionary compexes and magmatic arcs (24, 25, 41, and 42) have already

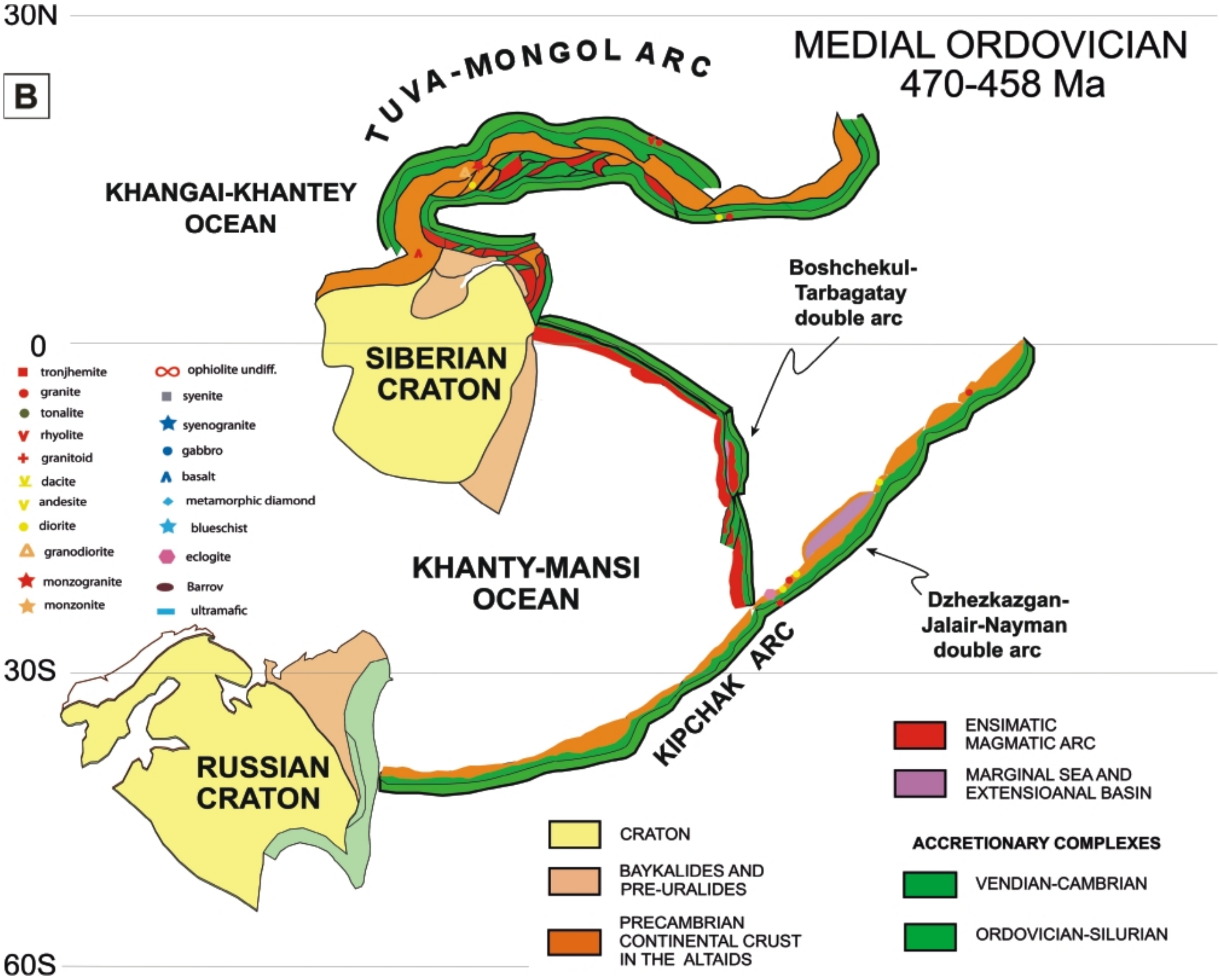

Figure 8B: Reconstruction showing the distribution of igneous and metamorphic rocks of medial Ordovician age listed in Table I of the first part of this paper (Şengör et al., 2014).

been imprisoned behind them by arc-shaving strike-slip faults (cf. Fig. 4) and thus had to cease their growth.

The formation of the South Mongol (43.3) Accretionary Complex and the magmatic arc resting atop it needs a special explanation. The main feature of this unit is that in spite of its position in front of a long-lived magmatic arc throughout the whole of the Palaeozoic (Tuva-Mongol Arc Massif) the accretionary complex does not preserve a full record of this subduction history. Its Vendian-Cambrian part is preserved only in the west (unit 42) as a wedge thining and wedging out eastwards (present geographical orientation). In the east, the oldest rocks in the accretionary complex are Ordovician. We assume that the Vendian-Cambrian accretionary complex originally extended along the whole length of the Tuva-Mongol Arc Massif, but owing to later strike-slip faulting, this accretionary compex was shaved off and transported coastwise part by part exactly as in the case of the future Altay units just mentioned above. The South Gobi Unit (44) functioned as a magmatic arc from the Cambrian to the Permian continuously, yet its accretionary complex spans a time interval of only from the Carboniferous to the Permian. We postulate that the earlier accretionary complexes had departed along strike-slip faults south-eastward along the Tuva-Mongol margin, and

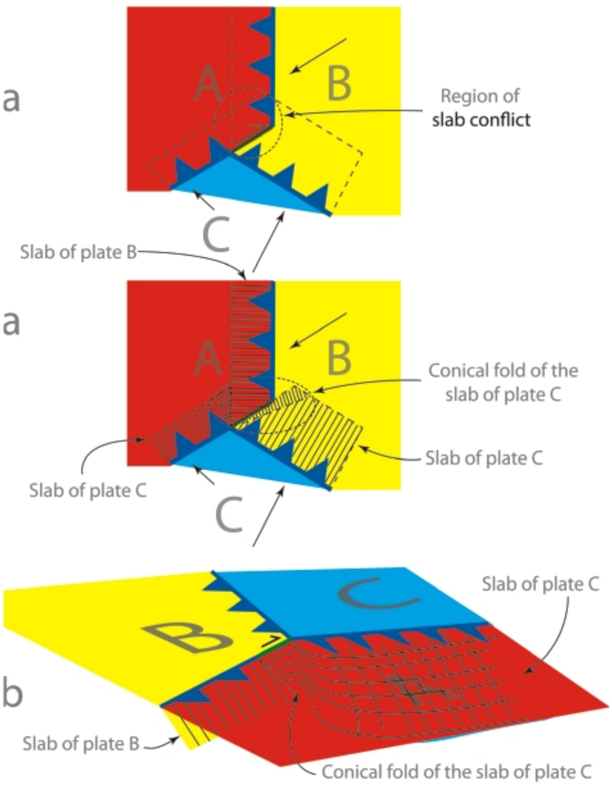

Figure 9: Sketch maps showing what might happen at depth at a triple junction similar to the one depicted on Fig. 8A. a) Map view: note that the slabs must interfere with each another at depth, if they are assumed to be flat, which is unrealistic. The dotted ellipse shows the volume in which a conical fold must be formed by the slab attached to Plate C. The slab of plate B accomodates itself into that slab. b) 3-D view of the conical fold of the slab of plate C and how the slab B descends through the opening created by the conical fold of the slab of the plate B (from Şengör, in press).

only since the Carboniferous an accretionary complex could grow here continuously. The western part of the South Mongol Unit, where the younger accretionary complex is trapped between two older ones, the complexity of the repeated shaving and translation of accretionary complex slivers along the Tuva-Mongol margin, has built an architecture resulting from the departed units having left behind some remnants.

Reliable modern isotopic ages are not abundant from the medial Ordovician but what Fig. 8B shows is a widening and a distinct separation of the two arc axes in the eastern parts of the Tuva Mongol Massif (present geographical orientation).

4.6 Late Ordovician (458–443 Ma: Figs. 10A and B)

The available palaeomagnetic and other geological data during this time allow us to retun to the single, continuous arc geometry for the Kipchak. In fact a geometry not dissimilar to the reconstruction offered in Fig. 10 a might have been also done for the medial Ordovician geometry that would have offered better tectonic continuity. The data would allow both interpretations. We have presented the more unlikely model simply because of its easier refutability and therefore greater information content (cf. Popper, 1994).

During the late Ordovician, strike-slip stacking occurred dominantly in the central part of the Kipchak Arc: In the Tien Shan – South Kazakhstan domain, units 1–4 formed a regular strike-slip multiple duplex structure while the Dzhezkazgan-Jalair Nayman Marginal Basin closed with a southerly vergence. Youngest rocks in the accretionary complexes of these units are medial Ordovician giving a *terminus ante quem* for the strike-slip repetition. The movement along the strike-slip faults continued later, with less displacement, while the domain was bending into the Tien Shan-Ural Orocline. Farther east (late Ordovician geographical orientation), in the present northern Kazakhstan, where the strike-slip stacking also began in the medial Ordovician, the arc has a more intricate structure. Fore some reason unit 7 did not move far with respect to unit 6 and units 8–12 were piled upon it. After the closing of the marginal sea in the double arc system of the Boshchekul-Tarbagatay System, unit 13 behaved like any other unit of the Altaid collage (Fig. 10A). During the later deformation, this eastern half of the stacked part of the Kipchak Arc nucleated the hinge of the Kazakhstan Orocline. In the late Ordovician and later, an accretionary complex formed along the southern side of the stacked region (unit 14). Vast intrusions of the arc-type late Ordovician – early Silurian granodiorites forming the arc of the unit 14 are spread across units 8–13 having clear cross-cutting relationships with older structures and providing a 'stitching arc' for the strike-slip stacked arc remnants in North-Central Kazakhstan.

The absence of the arc-related late Ordovician magmatism in the units of the northern part of East Sayan (26–29) is interpreted as evidence of a transform fault, connecting the Kipchak and the Tuva-Mongol subduction zones. Units of the northern part of the West Sayan and the southern part of the East

Sayan (30–35) pretty much stayed where they were during the earlier Ordovician. The positions of units 36–39 and 22–25 changed slightly from the medial Ordovician ones. Unit 40 maintained its relativly fast migration along the northern side of the Tuva-Mongol Arc creating space for formation of the South Mongol Accretionary Complex (43.3) as explained above.

If the picture presented in Fig. 10B is taken at face value, one would see that igneous activity on the strike-slip duplicated duplexes along the Kipchak Arc has taken a median position with respect to the duplex and defined a new magmatic axis. We take this as corroboration of the interpretation that the shear duplication took place above a single subduction zone.

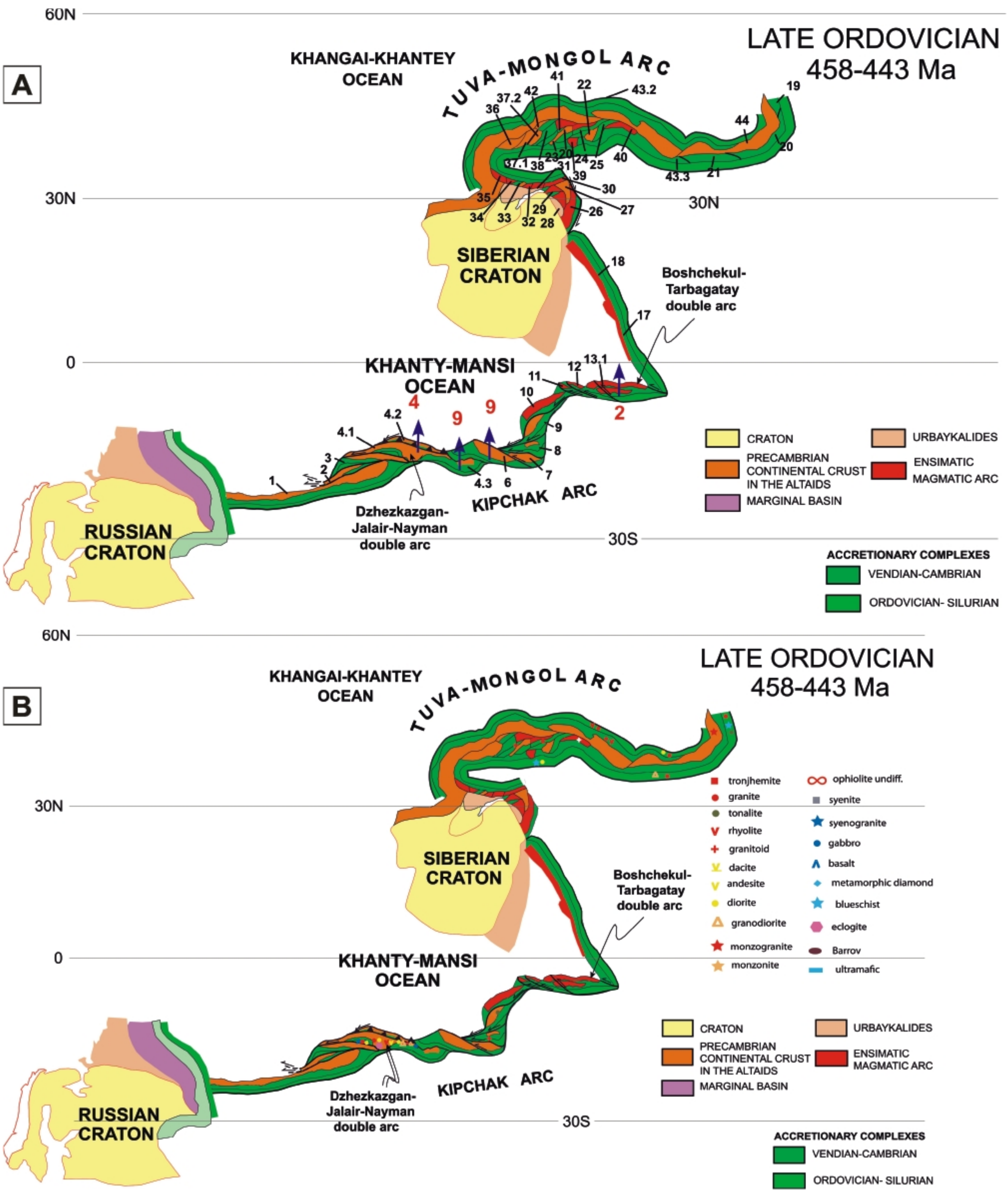

Figure 10: A. A possible late Ordovician reconstruction of the Altaids. Blue arrows indicate palaeomagnetic declination vectors with their tail at the appropriate latitude. They are keyed to Table I by the red numbers near them. B. Reconstruction showing the distribution of igneous and metamorphic rocks of late Ordovician age listed in Table I of the first part of this paper (Şengör et al., 2014).

By contrast, as the strike-slip duplication along the Tuva-Mongol Arc Massif led to such widening of the massif that two separate magmatic axes formed to the north and south of the enlarged continental mass, corroborating the double-subduction zone interpretation.

4.7 Medial Silurian (433–419 Ma: Figs 11A and B)

The most important event in the Kipchack Arc at this time was the beginning duplication of the Silurian magmatic front. Units 5 and 6 (the latter bears the east-facing Silurian magmatic arc: present geographical orientation) were left-laterally strike-slipped behind unit 4 (Fig. 11B). Simultaneously, the Central-North Kazakhstan collage (unit 7–13) started its motion along the northern side of unit 4 (Silurian geographical orientation: Fig. 11A). The dimunition of the Khanty-Mansi Ocean which had commenced already in the Ordovician was a result of the subduction of its floor under the Mugodzhar Microcontinent which now lies embedded in the orogenic system of the Uralides and the tightening orocline of the Kipchpak Arc. It is an interesting observation that the orocline that diminished the size of the Khanty-Mansi Ocean was almost the mirror image of the eventual Kazakhstan Orocline that was completed in the late Permian.

Major changes of the geometry of the Tuva-Mongol/North Sayan Arc System were underway. The West Sayan Orocline formed in the Silurian and appears completely closed in the early Devonian (Fig. 12A). This process can be subdivided into the three events. The first was the fast motion of units 36–38 and 22–25, 36–38, 40 and 42 moving as a single body. The Darkhat Unit (36) penetrated the ensemble of the units 33 through 35 and came into direct contact with the Siberian Craton isolating the units 32 through 35 behind it. Unit 39 then overtook units 23 and 36 through 38 during the second event in the formation of the West Sayan Orocline. The third event was the migration eastward of the hinge of the Tuva-Mongol arc. This migration apposed units 35 through 39 against unit 30 and thus formed the West Sayan Orocline by the late Silurian as shown by the sharp unconformity at the base of the shallow-marine clastics in the core of the orocline. This process also pushed the Barguzin microcontinent southwards which evoked the Patom shortening.

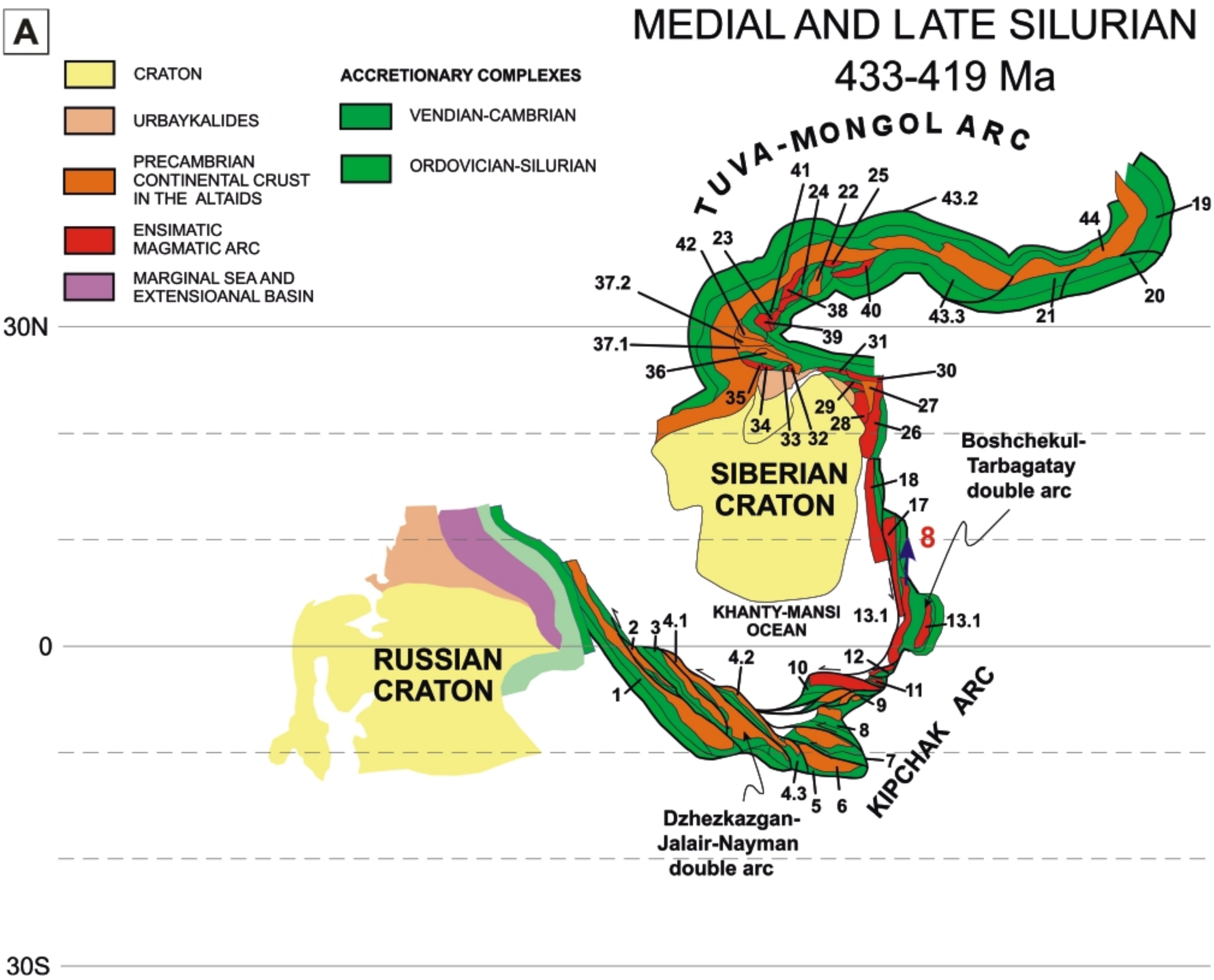

Figure 11A: A possible medial and late Silurian reconstruction of the Altaids. Blue arrows indicate palaeomagnetic declination vectors with their tail at the appropriate latitude. They are keyed to Table I by the red numbers near them.

In the medial Silurian unit 21 started its displacement along the Tuva-Mongol margin leaving behind units 19 and 20, as discussed above. Fig. 11B shows that the reliably isotopically dated subduction-related magmatics now crowd along the southern ('outer') margin of the Tuva-Mongol double arc and are concentrated (with the exception of a single monzogranite) in the southern accretionary complexes that had long turned into arc massifs by the migration of arc magmatic axes into them.

4.8 Early Devonian (419–393 Ma: Figs 12A and B)

The deformation of the Kipchak Arc continued in part as a result of the rotation with respect to one another of the Russian and the Siberian cratons and the westward movement of the Mugodzhar microcontinent as a result of the continuing opening of the Sakmara-Magnitogorsk Marginal Sea. Units 1–4 continued their left-lateral displacement with respect to one another (Fig. 12A). Here, for the first time palaeomagnetic observations necessitate the development of serious internal strain in units 1–4. Some of the Silurian and early Devonian sedimentary basins in southern Kazakhstan which are located along the boundary faults of these units have pull-apart origins. These pull-aparts may have been a consequence of the bending of the bounding strike-slip faults of the units. Units 5–12 advanced relatively farther to the south with respect to unit 4 leading to the duplication of the Silurian magmatic front in the Tien Shan-South Kazakhstan domain. The inner margin of the 'reverse' Kazakhstan Orocline began to re-open and the early Devonian magmatic arc that developed on that inner margin grew across units 6 to 18, providing a "stitching arc". The measured reliable isotopic ages on units 8 and 4.1 corroborate this inference (Fig. 12B), although the observations are as yet too few to define a continuous magmatic axis.

After the formation of the West Sayan Orocline, the presently sinuous Kuznetsk Fault, identified as a late Palaeozoic strike-slip fault, appears much less curved and thus a convenient path for the southward transport of units 22–25 and 40 along it as shown in Fig. 134. The late Palaeozoic structures of the Kuznetsk Sedimentary Basin occurring on the back side of unit 23 possess features of a foredeep basin in front of the Salair and Tym-Kolyvan fold-and-thrust Systems. We have earlier interpreted the basement of the basin as a Precambrian

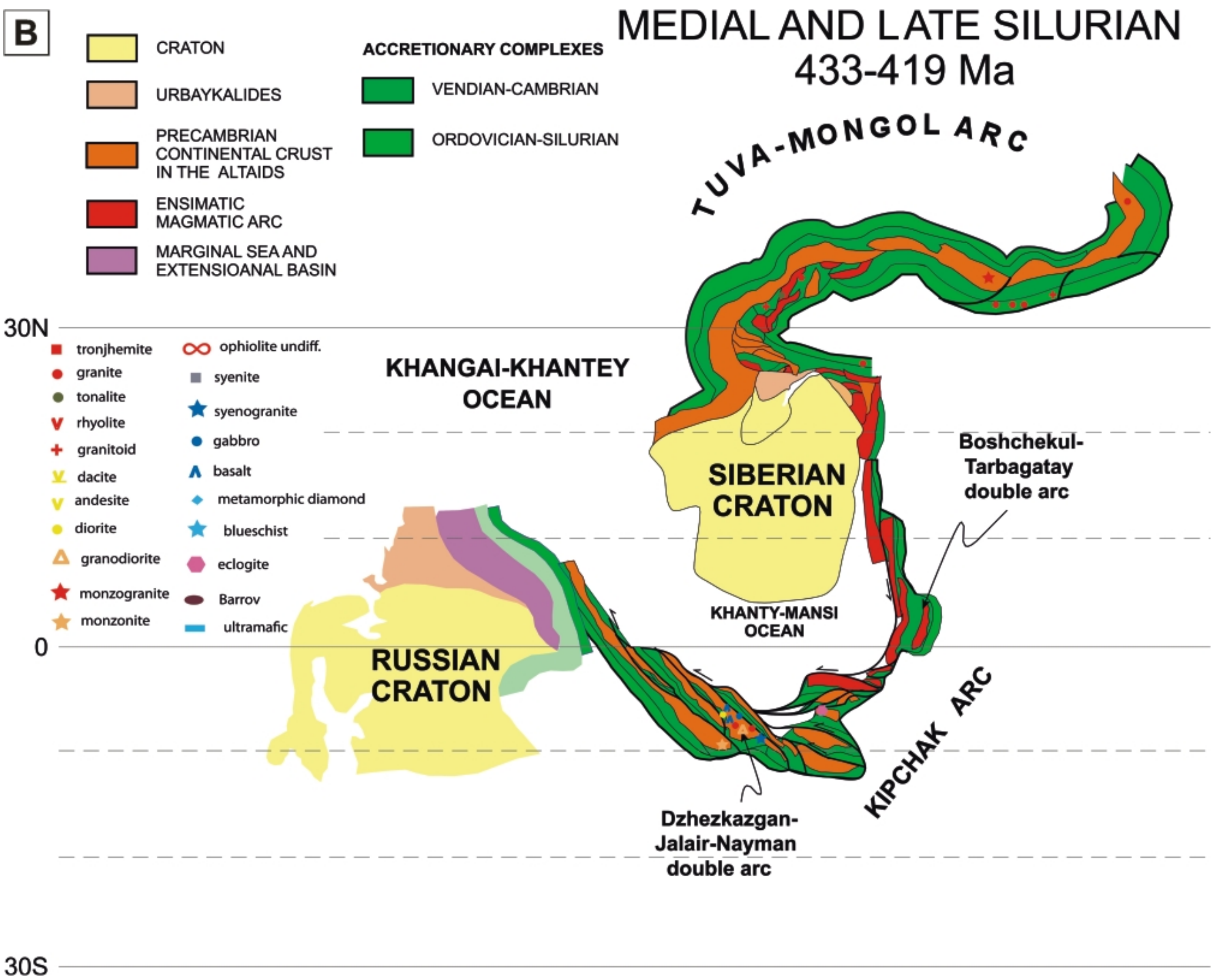

Figure 11B: Reconstruction showing the distribution of igneous and metamorphic rocks of medial to late Silurian age listed in Table I of the first part of this paper (Şengör et al. (2014).

block (Şengör et al., 1993) taking into consideration certain outcrops of high-grade metamorphic rocks, the age of which is poorly constrained, and mainly its roughly rectangular shape. The more detailed palinspastic reconstruction by Şengör and Natal'in (1996) allowed the inference that the Kuznetsk Basin may have formed as an extensional basin along the Kuznetsk Right-Lateral Strike-Slip Fault Zone in the early Devonian. This interpretation has been overlooked in the following studies, in which plume-related magmatism around the Permian/Triassic boundary was the focus of attention of the research (Dobretsov, 2003, Davies et al., 2010; Vladimirov et al., 2003; Buslov et al., 2010). Bimodal Devonian volcanics in the basin and a recently-dated mafic volcanic centre to its southeast (present geographical orientation: Fig. 12B) and early to medial Devonian basalt-rhyolite volcanics correlated with rocks representing a change from relatively thin shallow-marine karstic limestone to thick (more than 2000 m) marine clastic rocks (Babin, 2007), fit extensional interpretation better than our earlier interpretation. Seismic profiles indicate thickening of the gently dipping Devonian rocks to the southwest toward the folded Cambrian-Silurian structures of the Salair (Cherkasov et al., 2012) indicating the position of the depocentre of the initial extension. Recently, Dobretsov et al. (2013b) also accepted the Devonian extension in the Kuznetsk Basin but constrained it on the basis of modeling of the late Devonian successions (382–368 Ma) only, ignoring the earlier substantial subsidence. Other basins in the Altay-Sayan region (North and South Minusinsk, Tuva, Rybinsk etc.) filled up with Devonian and Lower Carboniferous clastics and alkalic and bimodal volcanics have probably the same origin.

In the early Devonian unit 21 moved fast along the South Mongol Accretionary Complex (43.1). Units 20 and 19 did not yet participate in the large scale strike-slip faulting. Unlike most units of the Altaids, the prow of unit 20 consists of younger accretionary complex material (Tym-Kolyvan) and its tail (Rudnyi Altay) of older accretionary complex material (Fig. 12a). To explain this we assume that the Devonian South Mongol (43.1) and Tym-Kolyvan accretionary complexes were forming in the rear of the moving unit 21 (see Fig. 12A) while the early Palaeozoic part of unit 20 kept its position at the northern side of unit 44 (present geographical orientation).

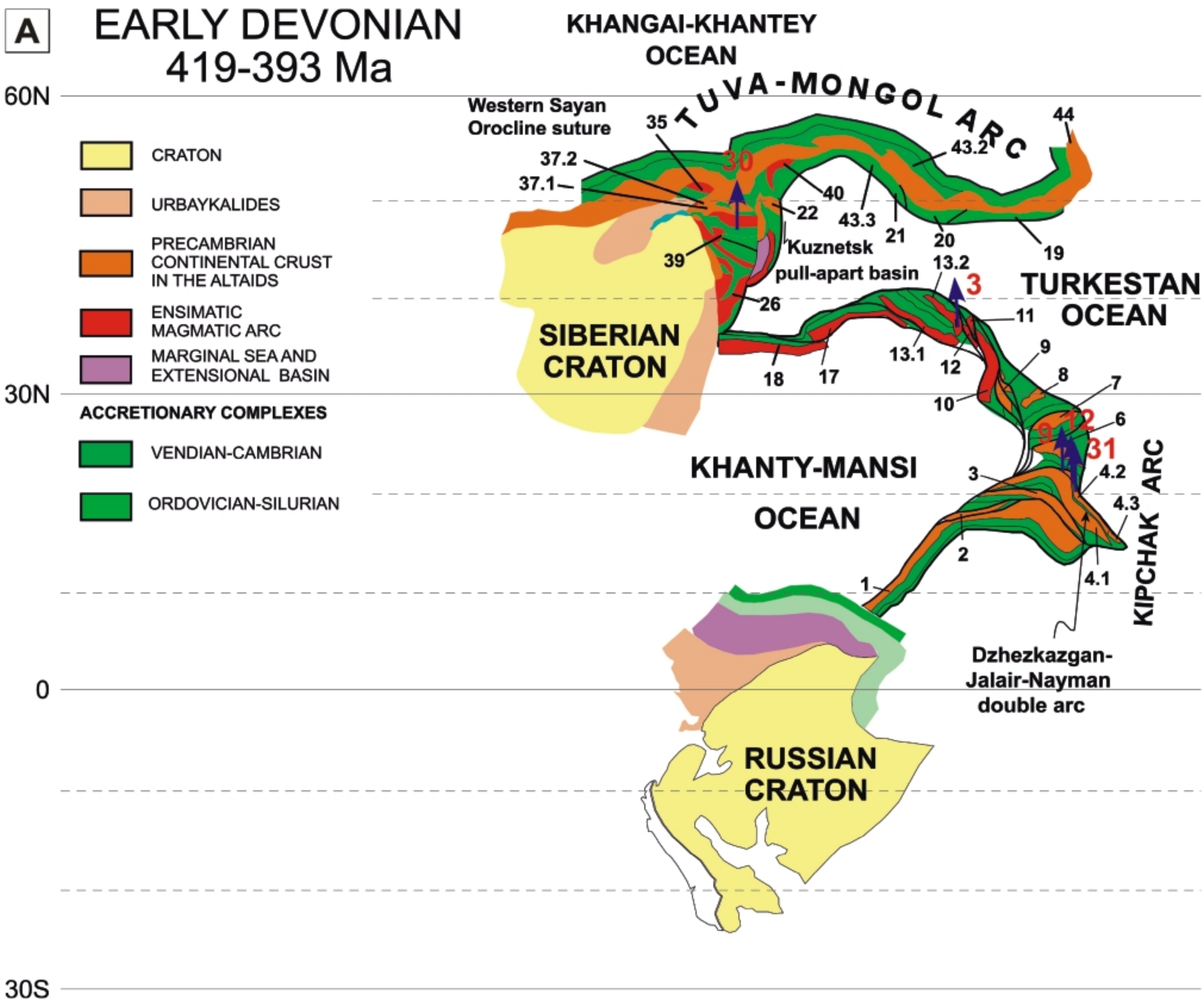

Figure 12A: A possible early Devonian reconstruction of the Altaids. Blue arrows indicate palaeomagnetic declination vectors with their tail at the appropriate latitude. They are keyed to Table I by the red numbers near them.

Fig. 12b shows that the magmatic picture of the Silurian did not substantially change, except that more subduction magmatism began invading the southern parts of the Altay *s. l.* (present geographical orientation). There are a large number of dated subduction-related materials and ophiolites near unit 18, corroborating our inference of its arc nature at this time.

4.9 Late Devonian (382–358 Ma: Fig.13a and b)

The North Caspian Basin began opening during the late Devonian as a southern and much enlarged part of the Sakmara-Magnitogorsk marginal sea (Fig. 13a). Although an extra-Altaid event, it exercised influence on the assembly of the Altaid collage and we can correlate its opening with certain events within the Altaids. The opening of the North Caspian Basin was probably coeval with the maximal opening of the Sakmara-Magnitogorsk marginal sea. It means that the Mugodzhar microcontinent had advanced farthest to the northeast with respect to the Russian Craton at this time. Its migration to the northeast acted to amplify the shortening caused by the rotations and actual approach of the Russian and the Siberian cratons towards one another. A consequence of these events was the retightening of the 'reverse' Kipchak Orocline, but at the same time the beginning formation of the Kipchak Orocline itself. It is important to emphasise that during the formation of these oroclines strike-slip faults played a greater role than bending of the units. The opening of the Japan Sea is a small-scale example of a similar phenomenon (Lallemand and Jolivet, 1985; Jolivet et al., 1994, 1995; Choi et al., 2013). Beginning with the Tournaisian, the closure of the Sakmara-Magnitogorsk marginal sea diminished the rate of shortening between the Siberian and the Russian cratons and hence the rate of deformation of the Kipchak Arc. If the rotation of the Siberian Craton with respect to the Russian Craton and eastward migration of the Mugodzhar Microcontinent in the same framework were steady, the late Devonian must have been a period of the highest rate of deformation of the Kipchak Arc. Units 7 through 13 of the Central-North Kazahstan domain ad-

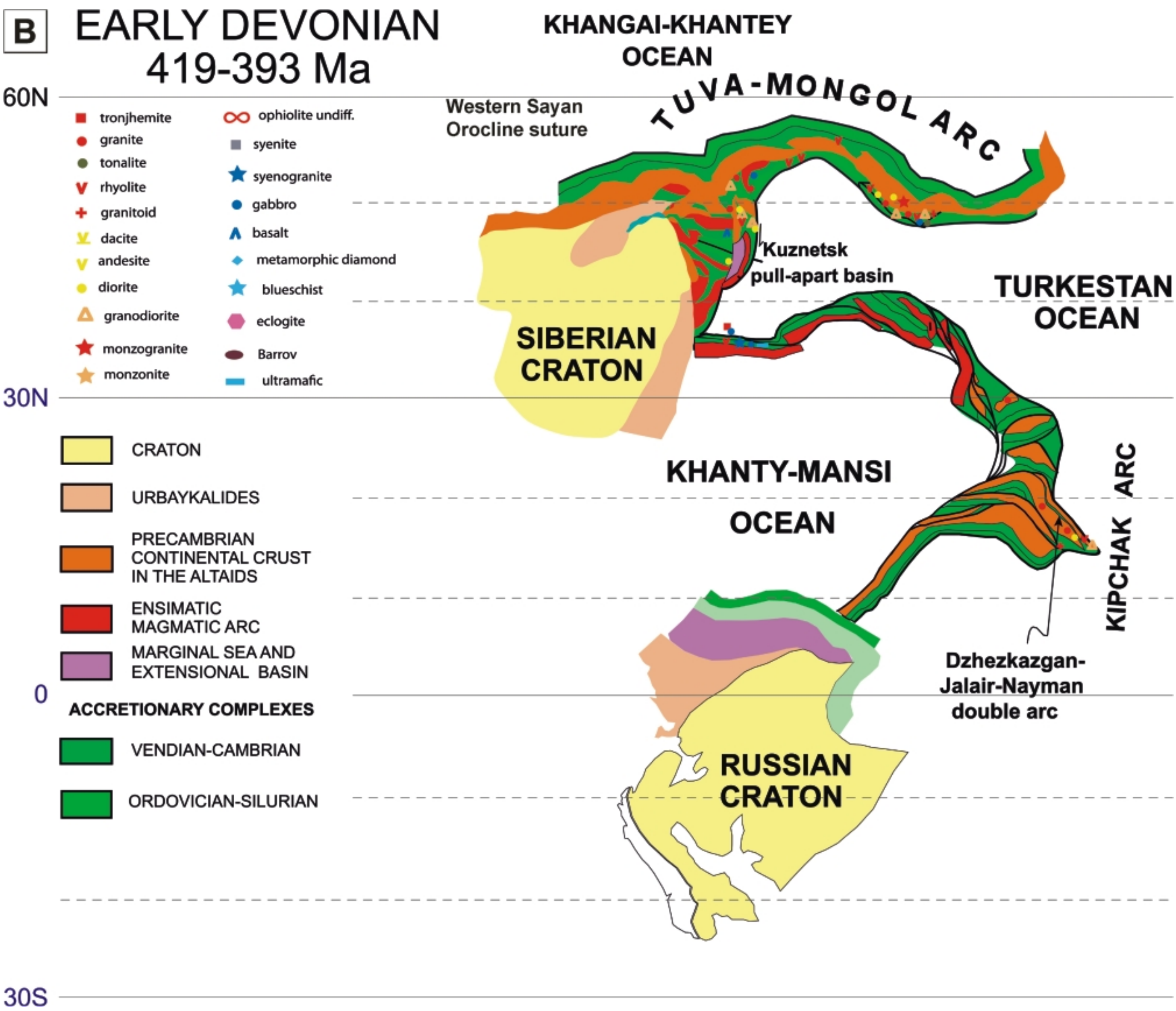

Figure 12b: Reconstruction showing the distribution of igneous and metamorphic rocks of early Devonian age listed in Table I of the first part of this paper (Şengör et al., 2014).

vanced to the west (late Devonian geographical orientation) almost into their present-day position. The domain moved along the Kaindy-Atasu left-lateral strike-slip Fault with respect to the Tien Shan – South Kazakhstan domain. Units 5 and 6 were enveloped by the strands of the Kaindy-Atasu Fault Zone. An *en échelon* array of the small sedimentary basins called the Sarysu-Tengiz Basins, and probably the larger Chu Basin, filled with Upper Devonian red beds, evaporates, grading up into Carboniferous – Permian shallow-marine and terrestrial, locally evaporate-bearing clastic and carbonate rocks, probably began forming along secondary extensional structures within the Kaindy-Atasu Fault Zone. This was also the time of formation of the short-lived late Devonian Uspensk Backarc Basin which later disappeared in the early Carboniferous. The basin is filled up with alkalic volcanics, black shales, and cherty limestones. A single trondjhemite has been recently dated isotopically within the arc behind which the Uspensk Basin had opened (Fig. 13B).

The southeastern margin of the Altay-Sayan collage was still a transform fault connecting the Tuva-Mongol and the Kipchak arcs, but units 17 and 18 had almost doubled back onto the Altay collage. The Kuznetsk Basin reached its maximum extent in the Givetian as shown by the widespread mafic volcanics of this age.

Unit 21 passed the whole length of the Tuva-Mongol Arc and reached the point of its final destination. It trapped in the west the narrow strip of Upper Devonian turbidites, black shales and cherts of the so-called Yustyd "Basin" which may be either an accretionary complex, or an forearc basin, of unit 40.

We believe that in the late Devonian unit 20 started its motion along the Tuva-Mongol Arc.

Isotopically well-dated arc magmatic rocks associated with the subduction of the Turkestan Ocean are all lined up on the accretionary complexes of the 'outer', i.e. southern side of the Tuva-Mongol Arc (Fig. 13B). The absence of subduction-related magmatics from the 'inner', part of the Tuva-Mongol Arc Massif is only a function of sampling bias as there are magmatics of late Devonian age dated by stratigraphic methods there.

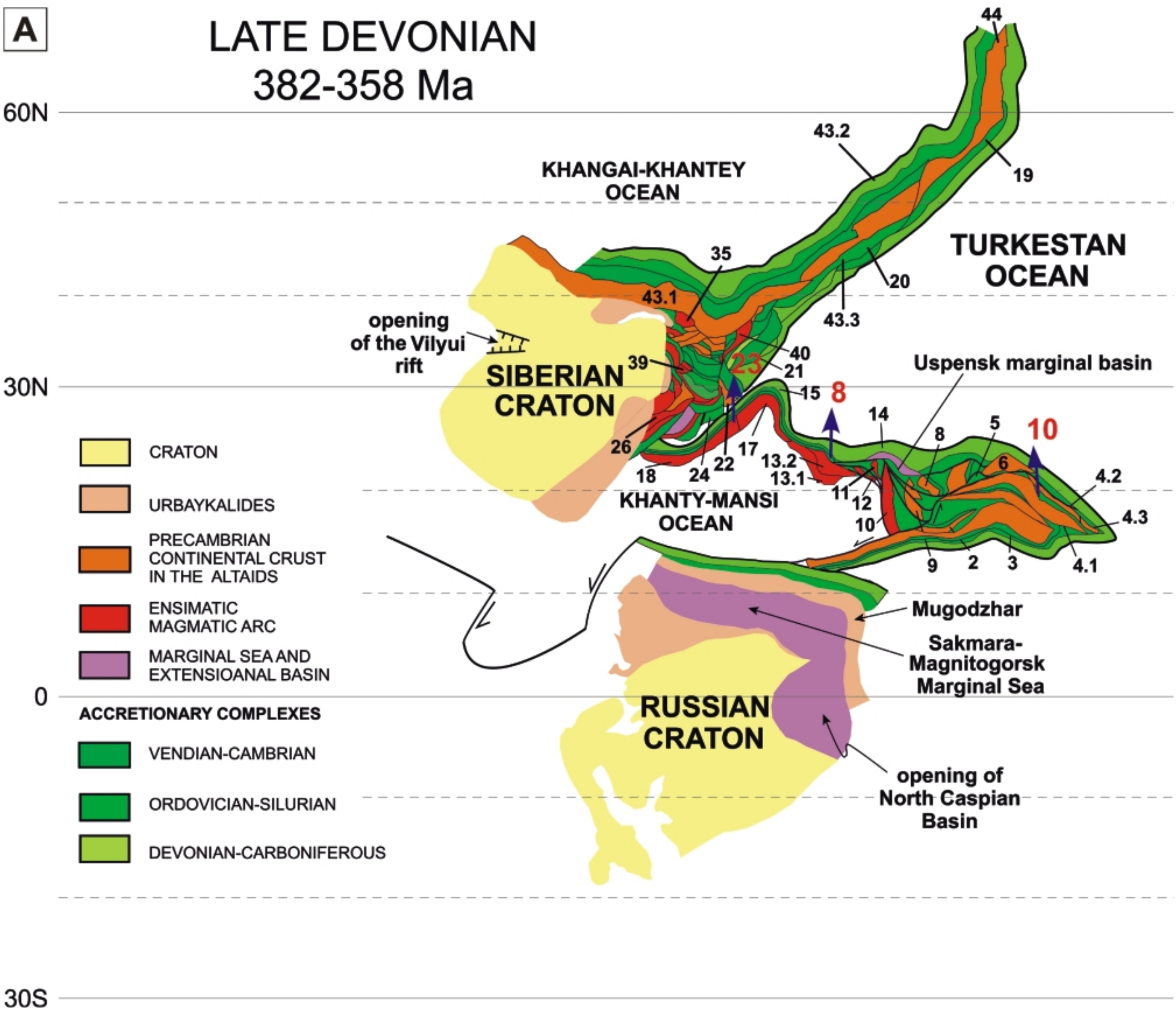

Figure 13A: A possible late Devonian reconstruction of the Altaids. Blue arrows indicate palaeomagnetic declination vectors with their tail at the appropriate latitude. They are keyed to Table I by the red numbers near them.

4.10 Early Carboniferous (358–323 Ma: Figs 14A and B)

This is the first time during which the Altaids west of Mongolia began to acquire a likeness to their present configuration. If a time machine had been able to take us back to the early Carboniferous and if an intelligent being of those days could take us on an excursion from the southern Urals to the Altay *s. l.*, we would be able to convince ourselves that we are indeed within the Altaid realm. By this time the 'reverse' Kazakhstan Orocline had been turned completely inside-out and the Kazakhstan Orocline had fully formed and already filled in with accretionary material, mostly flysch. In the Central-North Kazakhstan domain of the Altaids, the Zharma-Saur Unit (18) was strike-slipped behind unit 13 (Fig. 14A). Unit 17 was created as a result of shaving off a part of unit 13 by unit 18. Such a generation for unit 17 we reconstruct according to the following structural relationships: Structural trends in the northern part of unit 13 (present-day geographic orientation: Fig. 1) strike against the boundary of unit 18 at right angles (Fig. 1). It is easy to notice that a large piece of the northeastern part of unit 13 has also been shaved off because the Maikain-Balkubek Suture between units 13.1 and 13.2 is truncated in two places by the southwestern boundary of unit 18. From these relationships we conclude that unit 17 which is now located beneath the Western Siberian Basin is the displaced part of unit 13.

A conspicuous anomaly within the structure of Kazakhstan is a fragment of an early Ordovician accretionary complex overlain by a magmatic arc (northern part of unit 15, Fig. 14A) which sits in the midst of the huge medial to late Palaeozoic accretionary complexes of the core of the Kazakhstan Orocline (units 14 and 15). It could not be strike-slip stacked in the same way and at the same time as other Ordovician units (see Fig. 14A). To explain its emplacement we assume that unit 18 was divided into two segments by a right-latral strike-slip fault as shown in Fig. 14A. The strike-slip movement of the accretionary complex was accommodated by thrusting in the west. The Karaganda asymmetric sedimentary basin for-

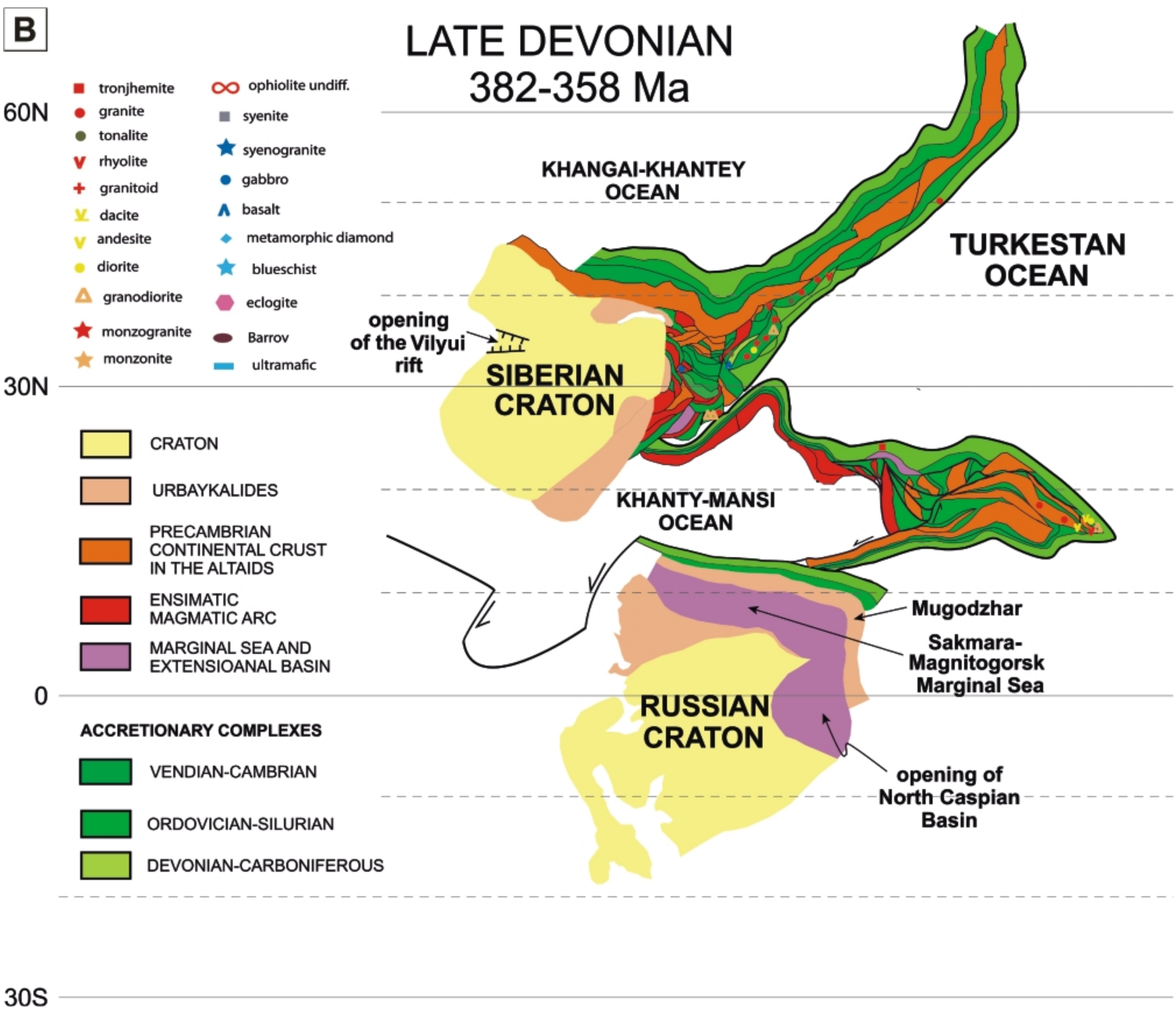

Figure 13B: Reconstruction showing the distribution of igneous and metamorphic rocks of late Devonian age listed in Table I of the first part of this paper (Şengör et al., 2014).

med in front of these thrusts. On the opposite side of the Kazakhstan Orocline, the Baratala Unit (4.3) became detached from unit 4.1 and moved towards the inner part of the orocline.

In the early Carboniferous, units 19 and 20 left their positions at the side of South Gobi Unit (44) and moved fast along the Tuva-Mongol Arc to their present-day locations. These large-scale displacements derived from structural relationships of the Altay-Sayan Units are in some degree supported by other lines of evidence. First, in the southern part of the Ob-Zaisan-Surgut Unit (19), typical accretionary complex rocks are mixed in the mélange with Devonian to early Carboniferous island arc volcanics. Our field investigation there in the summer of 1993 showed that this mélange had formed mainly through strike-slip tectonics. A long and wide belt of Carboniferous turbidites separates the mélange zones from the neighboring Devonian – early Carboniferous magmatic arc of unit 20 to the east (present geographic orientation). This arc thus could not be the source area for the arc-type volcanic inclusions in the mélange. We must look for the source area farther to the east (present geographic orientation) and the South Mongol Accretionary Complex invaded by the Devonian – early Carboniferous magmatic arc is the most appropriate place for it.

The second line of evidence concerns the discrepancy between the Cambrian through the Permian arc of unit 44 and the Carboniferous through Permian age of its associated accretionary complexes as discussed above. This is explained by the strike-slip shaving of the units 19 through 21 to remove the earlier accretionary complexes from in front of their arcs.

At its current position, unit 20 trapped Devonian – early Carboniferous turbidites containing tectonic lenses of dolerites, gabbros and ultramafic rocks in the east. We regard these rocks as fragments of the youngest portion of the accretionary complex of unit 21. Its structural position is the same as the position of the Yustyd 'Basin' of unit 40.

During the early Carboniferous South Gobi Unit (44) was detached from its original place and strike-slipped right-laterally with respect to the Tuva-Mongol Arc Massif (43.1). As a result of this displacement, the South Mongol Accretionary Complex was truncated in such a way that at present the late Devonian – early Carboniferous part of the accretionary complex wedges

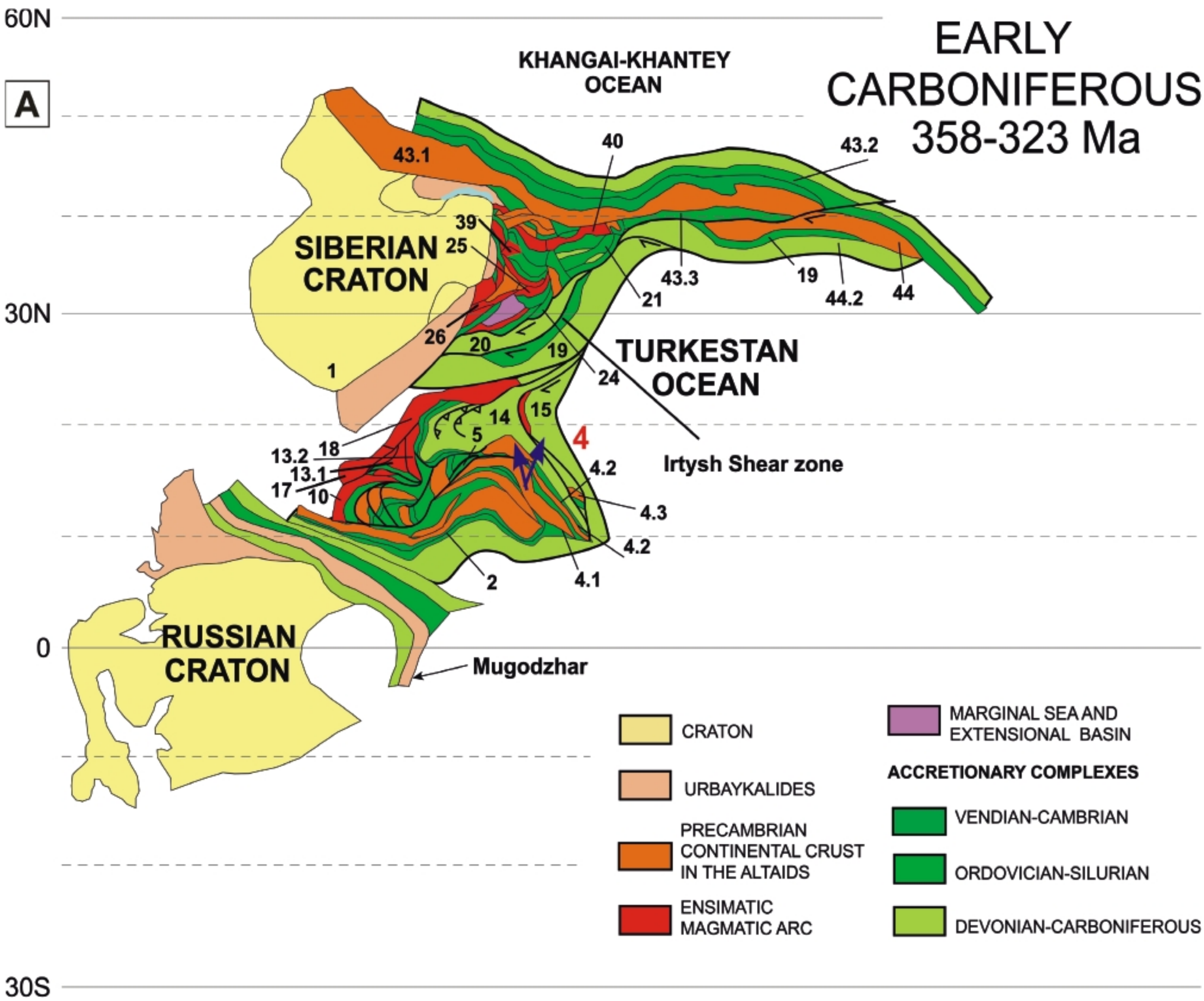

FIGURE 14A: A possible early Carboniferous reconstruction of the Altaids. Blue arrows indicate palaeomagnetic declination vectors with their tail at the appropriate latitude. They are keyed to Table I by the red numbers near them.

out eastwards. Although much larger, this geometry is similar to the geometry of the youngest portions of the accretionary complexes in units 40 and 21.

In the western part of unit 44 Silurian–Lower Devonian turbidites may represent at least a part of the accretionary complex of the Khangai-Khantey side dragged along with the South Gobi Unit when it slipped into its present position as shown in Fig. 14A. It is possible that a part of the Devonian – early Carboniferous accretionary complex, which we assigned to the South Mongol Unit (44), may belong to the South Gobi Unit, but structures at the southern boundary of the unit 43.3 rather indicate a first-order truncation. In the east (present geographic orientation) the youngest rocks that can be interpreted as an accretionary complex are Middle Devonian and they are intruded by the late Devonian – early Carboniferous granites. Therefore there is no way to continue to the east the accretionary complex of the South Gobi Unit in full, which one would have expected if the unit 44 had dragged its Khangai-Khantey Accretionary Complex (i.e. a part of unit 43.2) with it. From this we conclude that the South Gobi Unit left its accretionary complex behind as it moved along the strike-slip fault bringing it southward with respect to the Tuva-Mongol Unit. Our current interpretation of this left-behind accretionary complex is that it became in the Mesozoic the Okhotomorsk 'Microcontinent' of the Okhotsk sea-floor as shown by Bindeman et al. (2002).

The distribution of igneous and magmatic rocks that have been dated isotopically mostly using zircons and Ar-Ar method since Şengör and Natal'in (1996) had been published shows that the subduction-related rocks are confined to the east (south in the present geographical orientation), because that was the only active subduction zone left in the western part of the Altaid edifice. Only one granodiorite and one monzogranite were dated from unit 18 which raises the possibility of having an east-dipping (early Carboniferous geographical coordinates) subduction zone here. More observations are needed to delineate it, but it is a most exciting possibility.

Many well-dated rocks now exist along the western part of the Tuva-Mongol 'outer' side continuing into unit 19 (Fig. 14B). Two gabbros are near the right-lateral strike-slip fault separating the South Gobi Unit (44) from the rest of the Tuva-Mongol

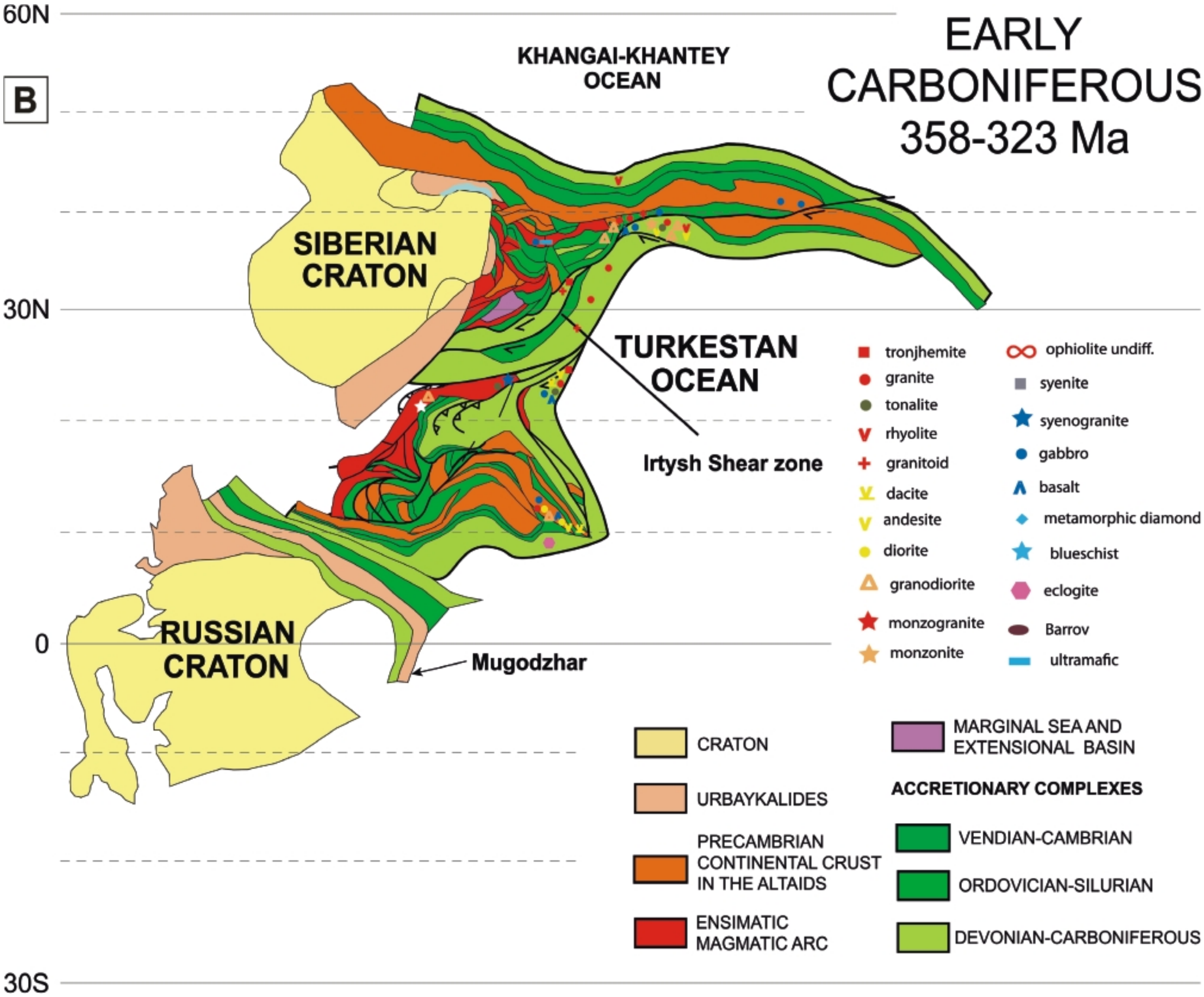

FIGURE 14B: Reconstruction showing the distribution of igneous and metamorphic rocks of early Carboniferous age listed in Table I of the first part of this paper (Şengör et al., 2014).

Unit and were probably consequences of the extension related to that shear motion. In the inner side of the Tuva-Mongol Unit a single rhyolite has been dated.

4.11 Late Carboniferous (323–298 Ma: Figs. 15A and B)

By the medial Carboniferous, the Tarim Block and some part of Beishan Unit had commenced their collision with the Altaids (Fig. 15A) and choked the subduction zone to the south of units 15 and 20 forming a suture (indicated by ladder symbol in Figs. 15A and B). The Altaid collage thus neared the end of its agglomeration, although in the period covering the rest of the Carboniferous plus the interval to the medial Triassic, the collage suffered a tremendous amount of internal deformation. We see this also in the increased amount of alkalic igneous activity within the collage lining up along the major strike-slip faults (syenogranites in Fig. 15B). The main tectonic problem of the late Carboniferous reconstruction is the establishment of the large-scale right-lateral displacement between the Altay-Mongol domain on one side and Tien Shan – South Kazakhstan and Central-North Kazakhstan domains on the other. In other words, a huge strike-slip displacement took place between the Russian and the Siberian Cratons. This displacement follows from the logic of our reconstruction namely, to emplace unit 19 to its present position we must displace the Kazakhstan Units as far to the north as is necessary to make space for unit 19. The associated deformation was mainly concentrated in the Gornostaev Shear Zone, separating the

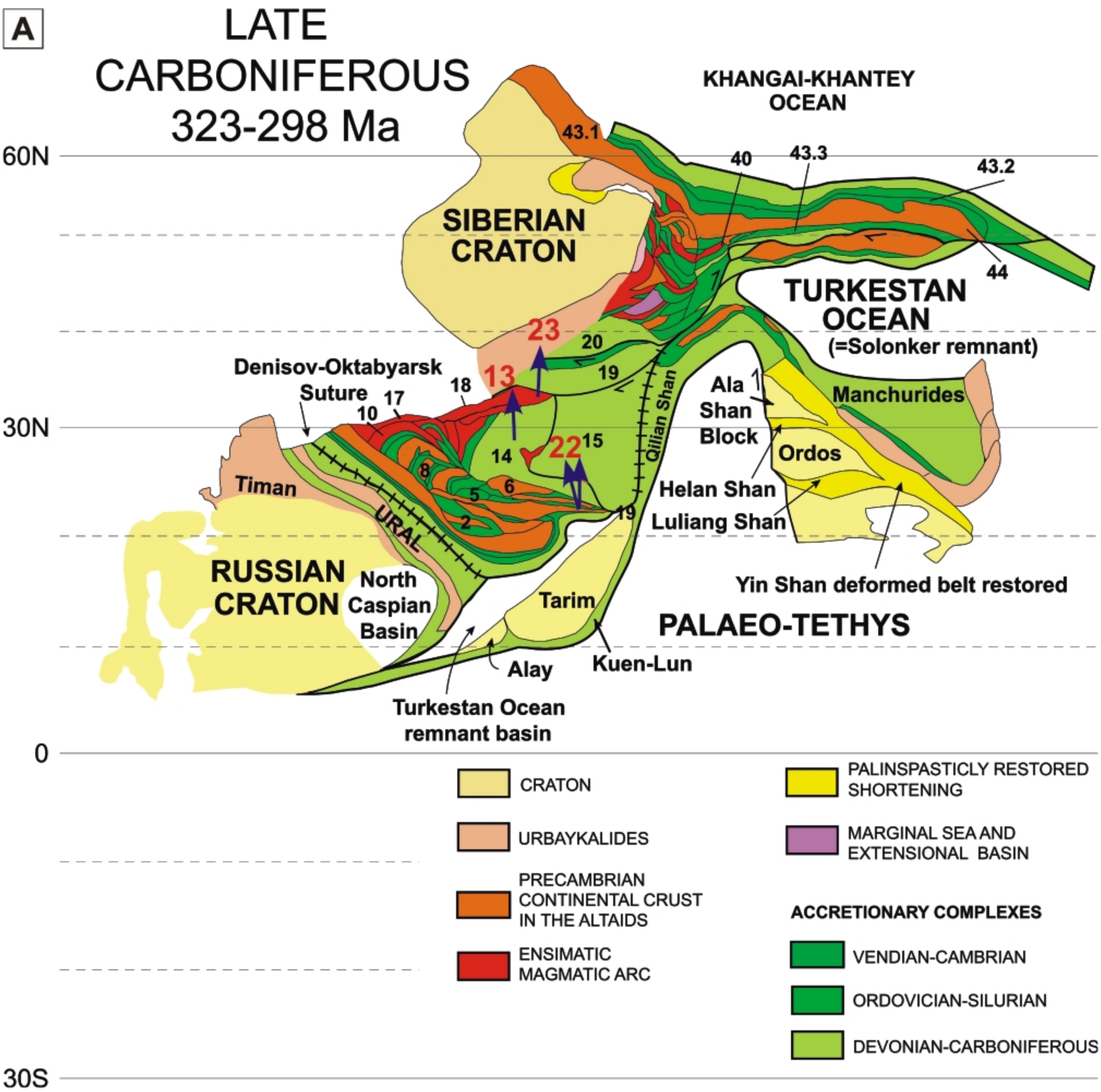

Figure 15A: A possible late Carboniferous reconstruction of the Altaids. Blue arrows indicate palaeomagnetic declination vectors with their tail at the appropriate latitude. They are keyed to Table I by the red numbers near them.

Zharma-Saur (18) and the Ob-Zaisan-Surgut (19) units. We assume also a large displacement along the Irtysh Shear Zone along which unit 19 moved to its final destination. However, Carboniferous structures from within scattered late Palaeozoic basins within the Kazakhstan collage, such as the Tingiz and the Chu basins, suggest that the right-lateral shear probably was much more widespread and affected the entire collage. The declination rotations seen in our palaeomagnetic data in the Tien Shan – South Kazakhstan and Central-North Kazakhstan domains from now on are all due to the internal deformation of the collage by means of these large strike-slip systems some of which to this day localise seismicity in Central Asia.

The Kazakhstan Orocline was tightened further and filled up with sediments laid down on remnant oceanic crust in the core of the orocline. The continuous tightening of the orocline led to hidden subduction, i.e. subduction beneath two collided accretionary complexes during their post-collisional convergence and shortening. Notice in Fig. 15B how gabbros, granodiorites, granites and trondjhemites line up beautifully defining an arc where there is no apparent subduction on both sides of unit 15. These are the places of the activity of hidden, sub-accretionary-complex subduction zones similar to the Jurassic arcs on the west side of the Songpan-Ganzi System in eastern Tibet (Şengör, 1984; Şengör and Hsü, 1984).

Since the medial Carboniferous, oceanic crust completely disappeared in front of the magmatic arc of the Ob-Zaisan-Surgut Unit (19). Nevertheless, the arc-type magmatism continued in this unit and neighboring regions in the Carboniferous and Permian. It was widespread also in the Junggar region of the Junggar-Balkhash Unit (15). The absence of any

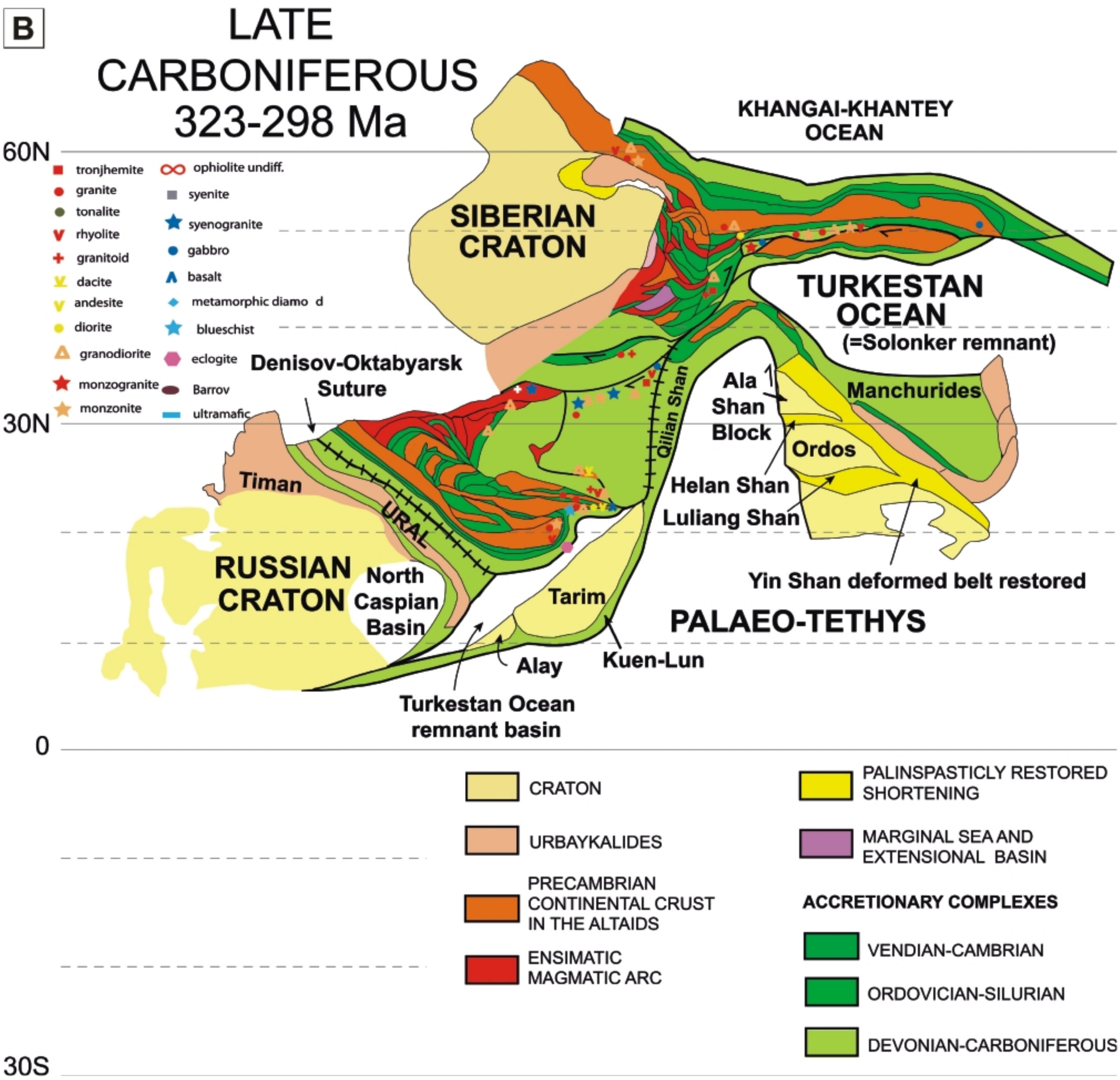

Figure 15B: Reconstruction showing the distribution of igneous and metamorphic rocks of late Carboniferous age listed in Table I of the first part of this paper (Şengör et al., 2014).

indicators of the late Palaeozoic oceanic crust or any rocks similar to trench sedimentary fills was a basis for the interpretation that all late Palaeozoic magmatism of Eastern Kazakhstan and Junggar had been collision-related. In the Junggar region of the Junggar-Balkhash Unit (15) late Carboniferous volcanics and granites are interpreted to be related to subduction, although all ocean had vanished there too from the surface by this time. *In our reconstruction it is seen that the subduction in the Qilian Shan was probably the source of this magmatism*.

In Qilian Shan and Qaidam regions of China there is at least a triple repetition due to left-lateral strike-slip faulting of an early Palaeozoic through Triassic accretionary complex and magmatic arc both of which being the easterly continuation of the south-facing (present geographic orientation) Kuen-Lun Accretionary Complex and Magmatic Arc (Şengör and Okuroğulları, 1991). In the Bei Shan region of China, early Palaeozoic rocks similar to present-day subduction-accretion complexes are separated by high-grade metamorphic rocks. The latter were interpreted as an arc massif and the structure of Bei Shan was explained in terms of an arc collision model (Hsü et al., 1992). We by contrast assume that the Beishan high grade metamorphic rocks are in fact the backstop of an early Palaeozoic arc and that the repetition of the early Palaeozoic structures was accomplished by strike-slip. When we restore the repetitions in the Qilian Shan and in the Bei Shan as it is shown in Fig. 15A, the total length of the accretionary complex and arc will be comparable with the length of the zone of late Palaeozoic magmatism in Eastern Kazakhstan and the Junggar region. This reconstruction shows that Qilian Shan Accretionary Complexes as well as the early Palaeozoic accretionary complexes of Beishan could tie together the accretionary complex of Kuen-Lun which is attached to the Tarim Block and the accretionary complexes and magmatic arcs of the Manchurides which were connected with the North China Block. The narrow central segment of this long arc system (restored Qilian Shan and Beishan) collided with the central part of the Altaids (unit 15 and 20). Because the central segment of the incoming arc (restored Qilian Shan/Qinghai Nan Shan/Bei Shan) was narrow, its arc magmatism invaded the adjacent Altaid units after the collision.

4.12 Early Permian (299–271 Ma: Figs 16A and B)

In the western part of the Altaids the right-lateral displacement between the Russian and the Siberian cratons along the Gornostaev and Irtysh Shear Zones continued in a right lateral sense briefly and then reversed, at about 272 Ma, earlier than the model of Şengör et al (1993) and Şengör and Natal'in (1996) predicted. The early Permian switch of the dextral motions in the Tuva Mongol domain to the early to late Permian sinistral displacements took place within the same structural framework of the tectonic units within the domain without creating any major structure. For instance, the youngest Altaid units (19 and 20) reveal a sharp oroclinal bend near Novokuznetsk as it is seen both in the geological structures and changes of trends of magnetic (Litvinova, 2000) and gravity anomalies (Petrov et al., 2004). Regarding dextral motions Buslov (2011) follows Şengör et al.'s (1993, 1994) idea (without, however, making any reference to the papers by Şengör and his co-authors) and shows on his map several northwest-striking dextral strike-slip faults running parallel to the strike of orogen. The Gornostaev Shear Zone (SW boundary of unit 19) as well as faults bounding unit 18 are included in this map. Unfortunately, structural descriptions of fault rocks, evaluations of displacements, and information on age of faulting are never discussed in his paper.

Using only stratigraphic data Şengör et al. (1993, 1994) and Şengör and Natal'in (1996) inferred the late Permian switch to sinistral motions along the Irtysh and Gornostaev shear zones. However, geochronological studies of the Irtysh shear zone confine the age of sinistral displacements within 283–265 Ma (Melnikov et al., 1998; Travin et al., 2001; Vladimirov et al., 2005). In the Chinese Altay, timing of strike-slip deformations is slightly wider between 290 and 245 Ma (Laurent-Charvet, 2002, 2003). Structural relations in the Fuyun area suggest the crosscutting relations between at least two systems of strike-slip fault, kinematics of all which is assigned to the sinistral type. At the same time, some faults reveal dextral sense of shear and their age is relatively old (265.6 ± 2.5 Ma). Interestingly, these NWW-striking faults are older according to structural relations although the age of the NW-striking Irtysh overlaps the ages of the Fuyun area. This reversal was also shown by Wartes et al. (2002) in a wider area, for the entire Irtysh–Gornostaev System including the pull-apart basins of Alakol, Junggar and Turfan.

In Permo-Triassic time, sinistral displacements along Irtysh shear zone switched to dextral again (Allen et al, 1995, 2006). We here adopt this revised timing.

Permian and Triassic events within the Altaids played a significant role in localising the West Siberian Sedimentary Basin later in the Mesozoic. The formation of the Nurol Depression as an extensional pull-apart basin along the right-lateral Irtysh Shear in the basement of the West Siberian Basin was probably the first step in this process. Unfortunately, data are limited on late Palaeozoic stratigraphy and the structural geology of this basin. Description of late Palaeozoic – Triassic redbeds and lagoonal sediments, smoothing an uneven relief on the Lower to Middle Palaeozoic rocks; late Palaeozoic gabbro and dolerite dykes, and reduced crustal thickness support our interpretation. At the northeastern side of the basin the age of coal-bearing clastics is late Carboniferous to early Permian indicating that stretching probably started earlier than the early Permian, consistent with recent revision downwards of the age of the onset of the left-lateral motion here. Northeast trending *en échelon* horsts, having abrupt terminations in the northeast and in the southwest, might indicate that extension was governed by north-trending right-lateral shear (present geographic orientation).

The accretionary complexes of Qilian Shan started their strike-slip repetition as a result of the movement of North China to the northeast (compare Figs. 15A and 16A).

According to palaeomagnetic data, since the Permian, North China rotated about 90° counterclockwise with respect to the Siberian Block. In the Permian it was far away from it (Fig. 16A). The final amalgamation of the North China and Siberian blocks occurred only in the medial or even late Jurassic (Van der Voo et al., in press). It is known also that the main part of Mesozoic convergence happened prior the medial Jurassic. After several attempts at plate tectonic reconstruction by various authors, it has become clear that it is extremely difficult to find a suitable suture for an ocean or oceans, separating Siberia and North China. All candidates for a suture, or sutures, have turned out to be either too old or too short in time if one tries to reconcile the age of suturing and the separation between North China and Siberia at the time. The usual approach to this problem has included two separate suggestions for a solution: The first suggestion was to account for the space betwen North China and Siberia by using in Inner Mongolia a late Permian suture, and secondly, to place the closure of the Mongol-Okhotsk Ocean into the Mesozoic times. The finding of a late Permian suture in Mongolia is easy although a schematic drawing of the palinspastic maps left behind certain geometrical complexities which we will discuss later. Knowing that the Mongol-Okhotsk Suture (*s.l.*) does not stretch farther to the west than 100°E and trying to accomplish the second step the authors employ the embayment shape and the scissors-like closure of the Mongol-Okhotsk Ocean (Khangay-Khantey Ocean in our reconstructions). Geological data are permissible for this idea because as already pointed out the Khangai-Khantey Unit includes the Upper Triassic turbidites as a part of the accretionary wedge in the east and via the

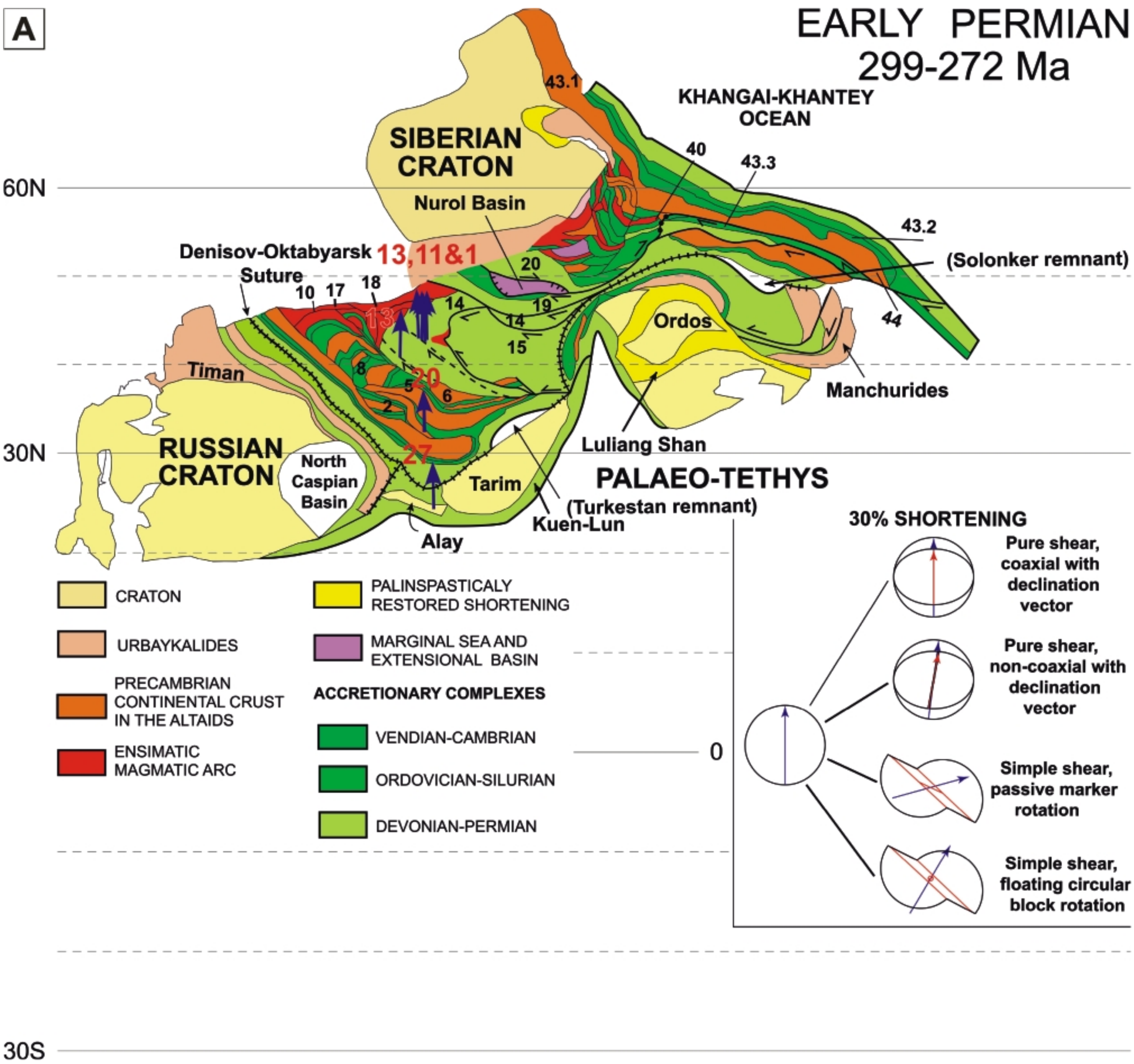

Figure 16A: A possible early Permian reconstruction of the Altaids. Blue arrows indicate palaeomagnetic declination vectors with their tail at the appropriate latitude. They are keyed to Table I by the red numbers near them.

strike-slip fault is connected with early – medial Jurassic Mongol-Okhotsk Suture (*s.s.*). Nevertheless, in contradiction to the geological data in most existing reconstructions, the pivot point for opening of the Khangai-Khantey Ocean is placed very far in the west. From our point of view this is impossible because in the Altay-West Mongolia Units there are no prominent east-west trending compressional structures of late Palaeozoic – early Mesozoic age to accommodate the 90° rotation of the Tuva-Mongol Arc. We here follow Şengör and Natal'in (1996) and Van der Voo et al. (in press).

Fig. 16B shows that alkalic magmatism further spread in the western part of the Altaid collage and again mainly along the major strike-slip systems. These strike-slip faults have also rotated the palaeomagnetic orientations very considerably, in places up to 90°. The inset shows what sort of mechanisms may have accomplished these rotations. A bulk shortening with pure shear coaxial with the orientation of the declination vector will accomplish no rotation whatever. If pure shear is not co-axial with the declination vector, there will be rotation, but not major. Only simple shear accomplishes considerable rotations. The highest amount of rotation occurs if the palaeomagnetic observation site is located on a slat fixed at both ends on the sliding blocks (McKenzie and Jackson, 1986). This can rotate the palaeomagnetic declination vector almost 90°. But if the palaeomagnetic vector is assumed to be fixed to a free floating block in a fluid-filled shear zone, the amount of rotation will be half that of the fixed slats, if the floating block is circular (McKenzie and Jackson, 1983). If elliptical, the situation becomes somewhat more complicated (Lamb, 1987). If rotations occur above detachments (extensional or shortening-related) on pieces moving like pack-ice, then they become much more complicated, unpredictable without a knowledge

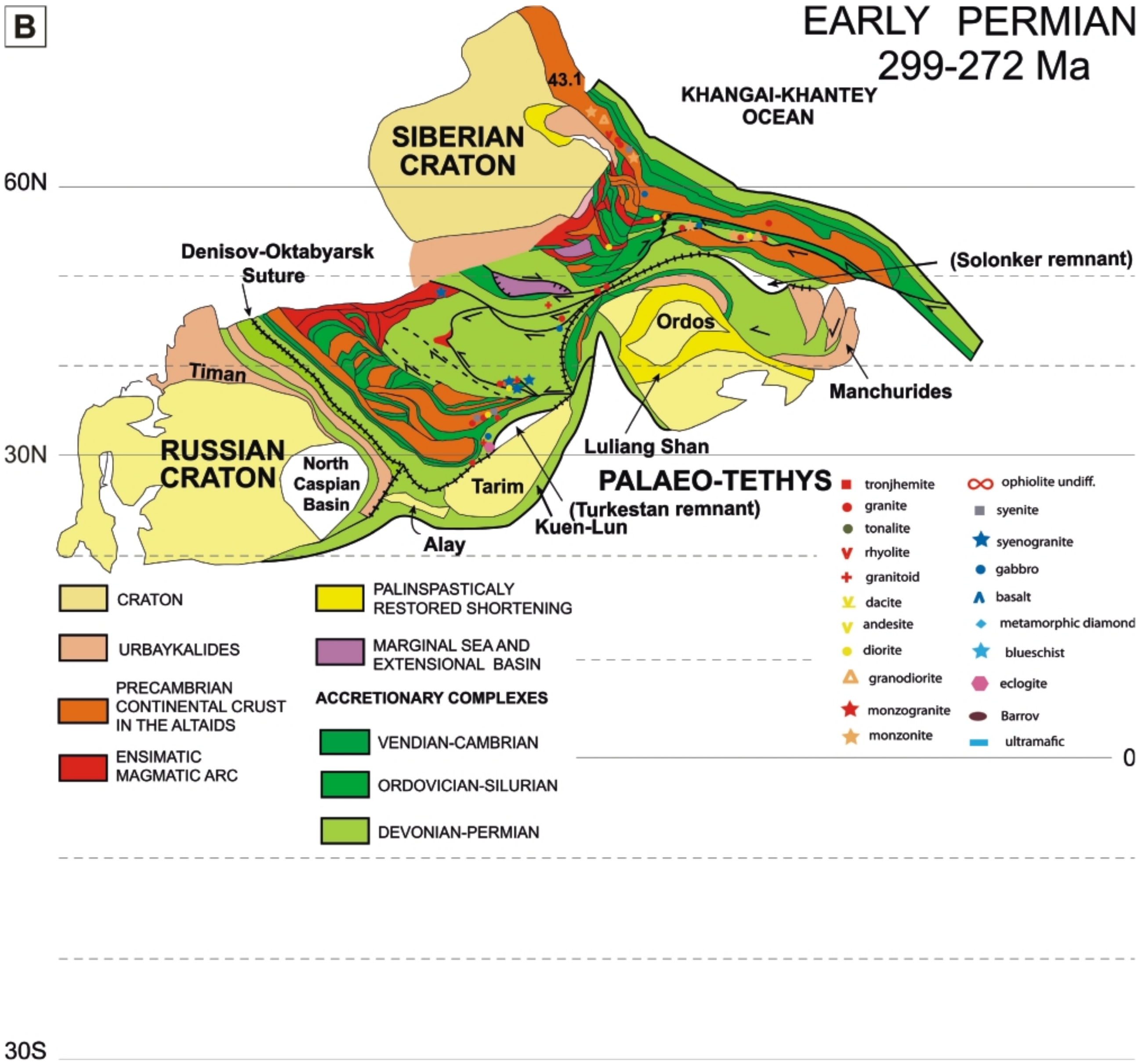

Figure 16B: Reconstruction showing the distribution of igneous and metamorphic rocks of early Permian age listed in Table I of the first part of this paper (Şengör et al., 2014).

of the exact geometry of the rotating blocks which requires detailed geological mapping in extensive areas. In one zone of shortening or extension, one can get rotations in both senses simultaneously greatly complicating tectonic interpretations (e. g., Kissel et al., 1987; Şengör, 1987). We have no reliable data on the detailed structural geology of the wider surroundings of the points where the palaeomagnetic observations we used were reported from. This shows how critical it is to combine palaeomagnetic work with structural work in a fairly extensive area around the points of palaeomagnetic observations.

In the Tuva-Mongol double arc, the southern subduction zone was still active, although living its last days. A lively magmatic activity is attested by the new isotopic age dates in unit 43. 1 above a slab dipping under Siberia. Van der Voo et al. (1999 and in press) were able to image this now vanished slab by seismic tomography under Siberia.

4.13 Late Permian (259–252 Ma: Fig. 17A and B)

By the late Permian, right-lateral strike-slip displacement between the Russian and the Siberian cratons had switched to left-lateral as mentioned above. It was concentrated mainly in the Gornostaev Fault Zone, but affected not only the entire Altaid collage but also the Manchurides (Fig. 17A).

The creation of the largest and deepest part of the basement of the West Siberian Lowlands, namely the Nadym Basin, seems related to this event (Fig. 17A). This Palaeozoic basin of some 5 km depth is in turn overlain by 5–9 km-thick rocks of the Mesozoic–Cainozoic Western Siberian Basin. The Nadym Basin was interpreted as a relict oceanic basin, taking into consideration the great thickness of the sedimentary fill, absence of angular unconformities throughout the Palaeozoic and Mesozoic succession, reduced thickness of the crust, and the absence in the crust of the so-called “granitic” layer. Nadym Basin and some smaller basins filled up with late Palaeozoic clastic rocks intercalated with volcanics and limestones on the trend of the Gornostaev Fault lie in a left-stepping pull-apart geometry (Fig. 17A). These rocks are intruded by dolerites and basalts. Judging from this arrangement of the basins, the Gornostaev Fault, and the loci of the late Palaeozoic magmatism here, we follow Şengör et al (1993) and Şengör and Natal'in (1996) in inferring an extensional origin for the Nadym Basin, as well as the other smaller basins, related to strike-slip along the Gornostaev Fault.

The left-lateral displacement along the Irtysh-Gornostaev Keirogen had brought the two segments of northern Asia it divided nearly to their present-day positions relative to each another as seen in Fig. 17A. The northern end of the Irtysh-Gornostaev Keirogen is located in the deep Nadym Basin (Fig. 17a). It is remarkable that the largest plateau basalt outpour

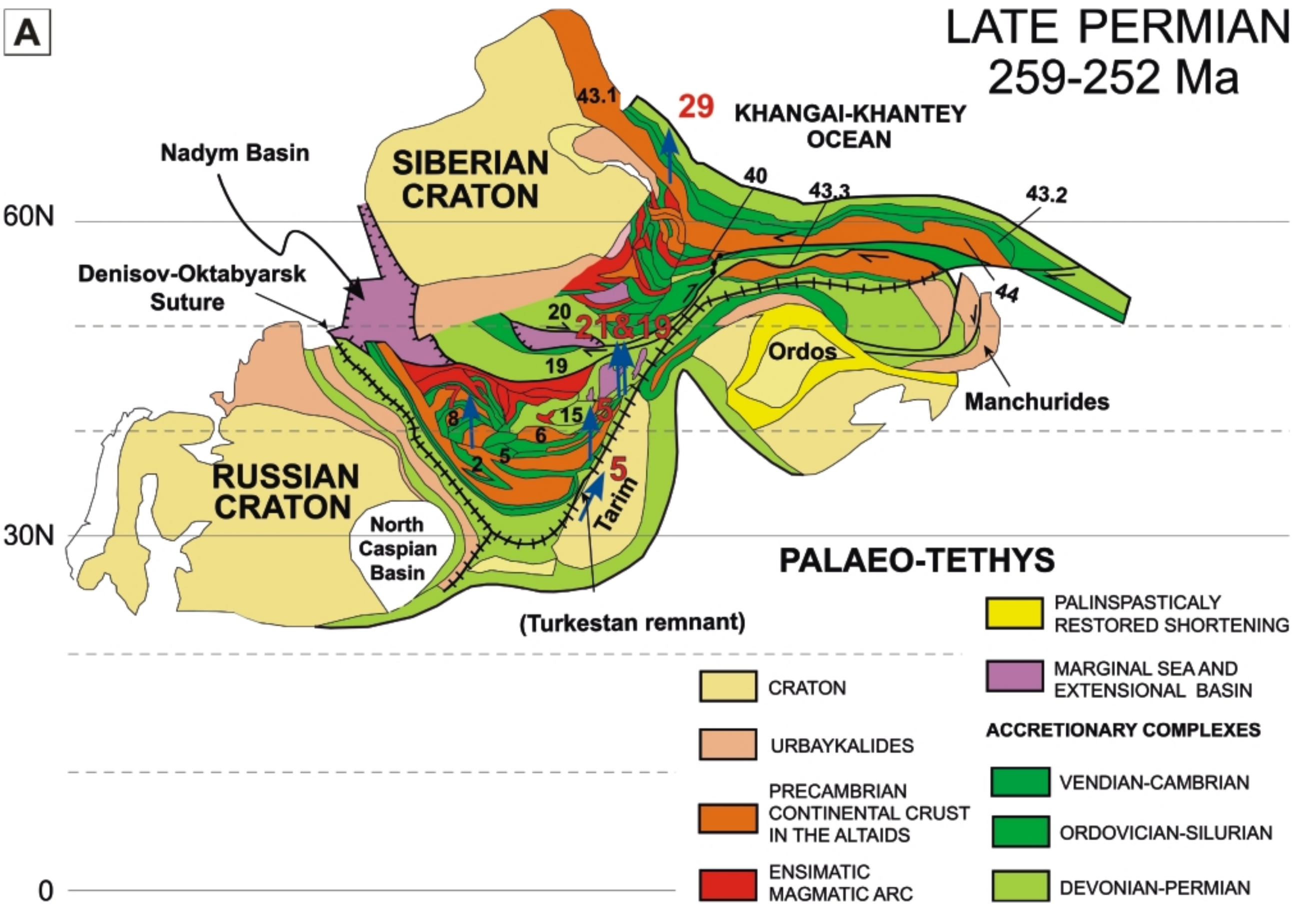

Figure 17A: A possible late Permian reconstruction of the Altaids. Blue arrows indicate palaeomagnetic declination vectors with their tail at the appropriate latitude. They are keyed to Table I by the red numbers near them.

in the entire Phanerozoic, the Tunguska traps of Siberia lies athwart the Nadym Basin and the Irtysh-Gornostaev Keirogen farther south. The total volume of the traps has been estimated somewhere between 2 million cubic kilometres (Milanovsky, 1976) and 4 million cubic kilometres (Masaitis, 1983). The time of eruption is often expressed to have been less than 1 Ma, but this is most unlikely in the face of the palaeontological evidence from the inratrappean sediments suggesting a duration of some 5 Ma (Hallam and Wignall, 1997, p. 136). This is corroborated by the most recently published compendium of isotopic ages we can find at http://www.le.ac.uk/gl/ads/SiberianTraps/Dating.html (seen on 15th December 2007) that span an age interval of some 4 Ma. The recent discovery of a Palaeocene palynoassemblage by Bandana Samant and co-workers (see Samant et al., Palynology and clay mineralogy of the Deccan volcanic associated sediments of Saurashtra, Gujarat: Age and Palaeoenvironments: http://www.ias.ac.in/jess/forthcoming/JESS-D-12-00328.pdf, last visited on 29th September 2014. The reported taxa are: *Intrareticulites brevis*, *Neocouperipollis* spp., *Striacolporites striatus*, *Retitricolpites crassimarginatus* and *Rhombipollis* sp.) within the Ninama sequence in Saurashtra in Gujarat supports the idea that the Deccan eruptions spread over an interval spanning at least a few million years). A similar time span must have been necessary for the eruption of the Siberian traps.

To visualise the possible connexion between the Tunguska trap eruptions and the extension, we here summarise an argument from Şengör and Atayman (2009): consider first a 3300 km long fast spreading ridge (roughly the N-S extent of the Tunguska trap province) with a spreading rate of 16 cm/a (about the rate of an ultrafast spreading ridge today), it would generate an oceanic crust of some 2,640,000 km^3 in one Ma (assuming a crustal thickness of 5 km). If the duration is extended to 5 Ma, the volume would grow to 13,200,000 km^3. The amount of offest along the Irtysh-Gornostaev Keirogen is about 2000 km and this is accomplished sometime during the Permian. Let us say that the extension took the entire time represented by the Permian (about 50 Ma and the rate of extension we get is thus 20 cm/a, equal to the fastest spreading known on earth: see above) and that the eruptions occupied only the last 5 Ma. This could give us an offset of some 400 km if we assume the rate of motion along the Irtysh-Gornostaev Keirogen to have been uniform. If this were all spreading along a ridge 3300 km long, the volume of oceanic crust generated would have been some 13,200,000 km^3. If we reduce the spreading rate or the time interval of eruptions by four times, we still get some 3,300,000 km^3; if we also halve the ridge length we get 1,150,000 km^3 which is near the lower estimate for the volume of the Tunguska trap volume. Now, imagine the eruptions distributed to many conduits instead of confining it to a single spreading centre and at the same time

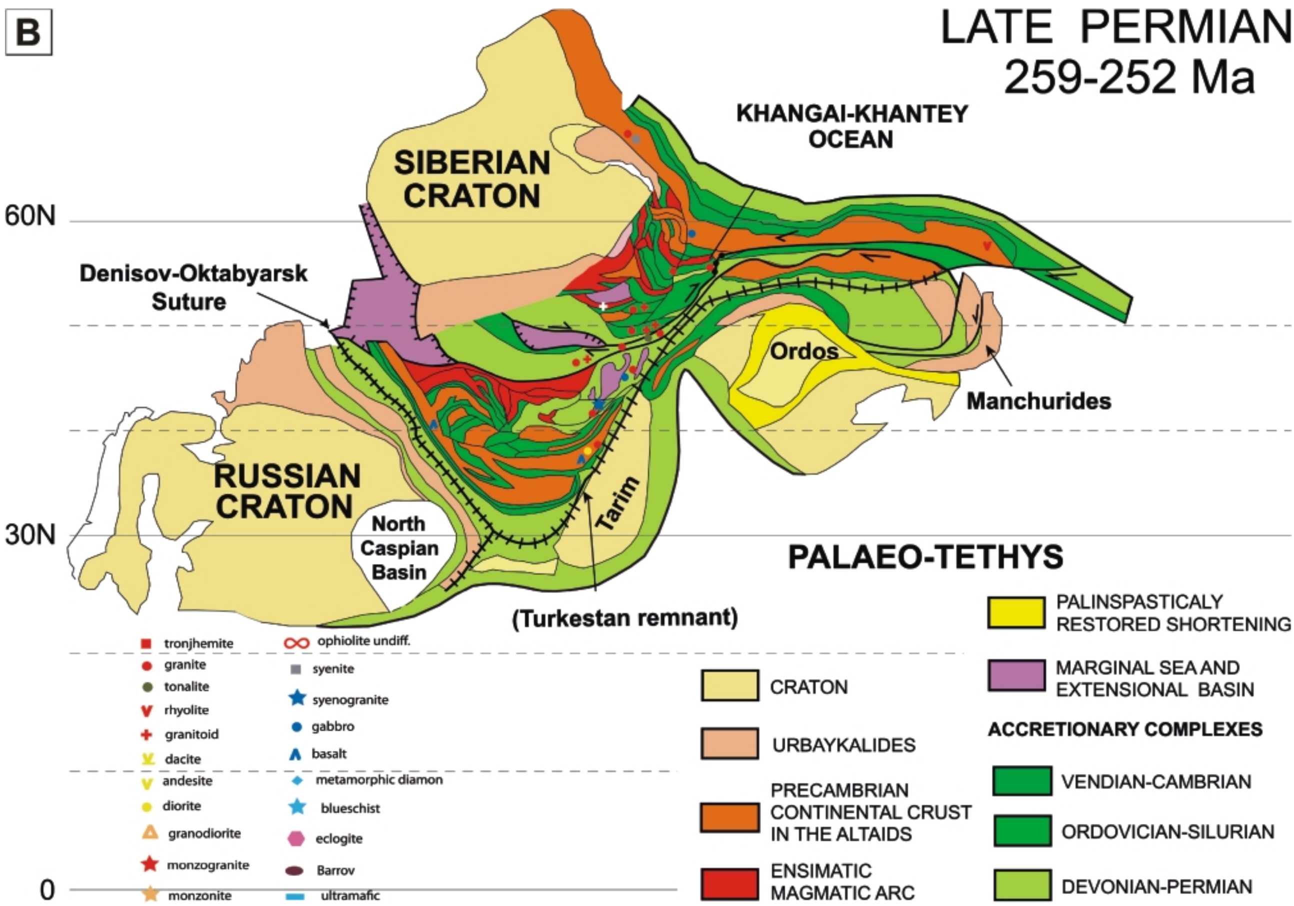

Figure 17B: Reconstruction showing the distribution of igneous and metamorphic rocks of late Permian age listed in Table I of the first part of this paper (Şengör et al., 2014).

honour the palaeontological dating by making the eruption interval some 4 Ma? We can reach the higher estimates for the amount of basalt only by lithospheric stretching without the help of a mantle plume. This does not mean that there was no mantle plume involved. It simply shows some of the possible implications of the large amounts of strike-slip faulting in the late Permian for the formation of parts of the West Siberian Basin and its magmatic accompaniment.

Analysis of the type and rate of sedimentation, arrangement of depocentres of sedimentation and their local structural control, spatial distribution of Permian and Triassic mafic-felsic magmatism (recently isotopically dated gabbros, syenogranites, granites in addition to the basaltic dykes previously known: Fig. 17B), rotations of structural trends in the Junggar and Irtysh Fault Zones, and palaeomagnetic data require an extensional origin of the Junggar, Turfan, and Alakol Basins located in a wide left-lateral shear zone between the Irtysh/Gornostaev fault pair and the Junggar Fault (Wartes et al., 2002).

In the late Permian, the Manchuride/Altaid suture at the Solonker Zone was finally completed (Fig. 17A). Fragmentation of the eastern part of the Manchuride Arc had started immediately after the first contact in the early Permian in the eastern part of Inner Mongolia and it continued into the late Permian owing both to the convergence of North China and Siberia and to the left-lateral strike-slip faulting right across the late Palaozoic Asia mainly along the Gornostaev Fault Zone and its easterly continuation into the Manchurides. The Manchuride Units were strike-slipped in a way which is very similar to the structural style of the Altaides. For the details of this reconstruction see Figs. 18–20 where we show the details of the early Triassic geometry of the Manchurides.

Newly-dated Permian arc-type volcanics, in addition to those previously known from geological relationships in the Tuva-Mongol Arc Massif indicate that the Khangai-Khantey Ocean remained open as it is shown in Fig. 17B.

4.14 The Mesozoic evolution of the Altaids

Western part. In this paper we do not deal with the intracontinental tectonics that post-dated the Altaid evolution, simply because much of it is buried under the Permo-Mesozoic cover of the West Siberian Basin greatly hampering a structural analysis, despite the recent availablitiy of abundant seismic reflexion profiles. It has long been known that the West Siberian Basin underwent significant extension as shown by the Lower to Middle Triassic basalts occurring in numerous narrow rifts. These extensional structures have been compared with the classical rift chains such as the East African taphrogen consisting of one major and a minor rift chain, but they resemble more the Basin and Range taphrogen of the Western United States (Numic subtaphrogen and the northern part of the Piman subtaphrogen) and northern Mexico (southern part of Piman subtaphrogen), the North Sea and the Aegean taphrgogens (Şengör and Natal'in, 2001). In West Siberia, the Triassic rifts are spread over an area of some 2.2 million square kilometres (Ulmishek, 2003). The largest of the individual rifts within this immense West Siberian Taphrogen, the Koltogor-Urengoy Rift, has a north-south length at least for some 2000 km as a more or less stright line, a geometry most unusual for ordinary rift chains (cf. Şengör, 1995). It is likely that such straight rifts in Western Siberia were actually nucleated on north-south striking Carboniferous to Permian strike-slip faults parallelling the Irtysh and the Gornostaev systems. As mentioned in the Part I of this paper (Şengör et al., 2014, p. 187) Lehmann et al.'s (2010, Fig. 1) attempt to rename the Irtysh-Gornostaev System discovered by Şengör et al. (1993) as the 'Transeurasian Fault' is inappropriate, not only because it violates the principles of priority by attempting to rename someone else's discovery without adding anything to it, but also because the Irtysh and the Gornostaev systems were probably not the only major strike-slip faults that provided rails on which the Si-

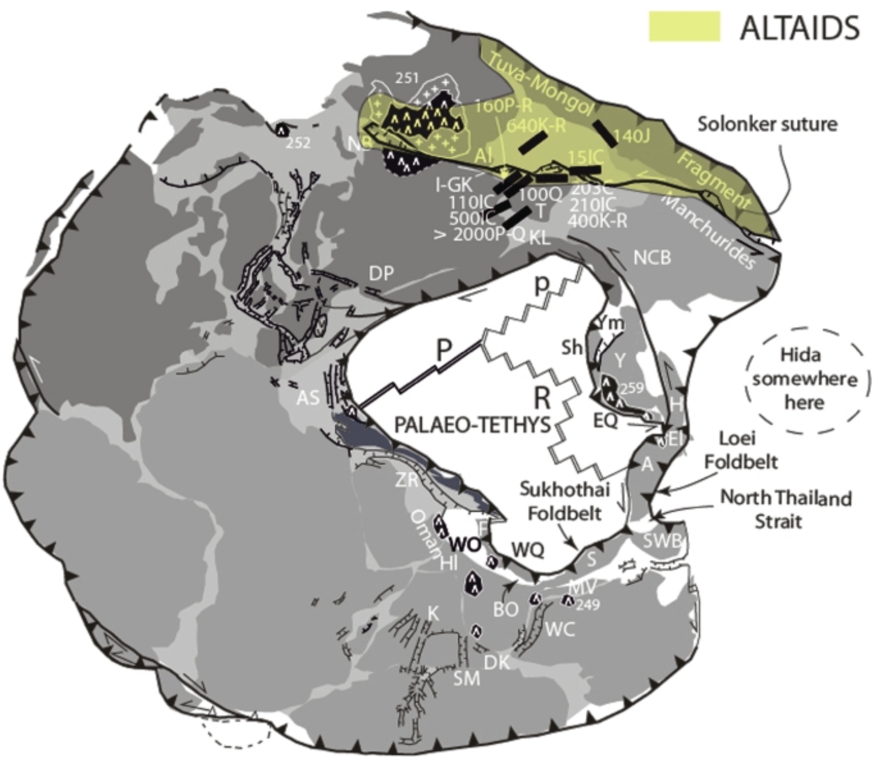

Figure 18: The tectonics of Pangaea at the end of the Permian (modified from Şengör and Atayman, 2009). Notice that the Altaids as whole are separated from the rest of the continent by the major Irtysh-Gornostaev Keirogen that extends so far east as to bound the Altaids against the Manchurides. The Irtysh-Gornostaev Keirogen is one of the largest strike-slip dominated belts of deformation in earth history that we are aware of. The cumulative offset along it amounts to thousands of kilometres.

berian and the Russia cratons moved with respect to one another during Permo-Carboniferous time and that almost the entire West Siberian area might have been a giant keirogen on which the later taphrogen became localised. Some of the rotations of the declination vector during the Permian as discussed above support this view.

The West Siberian Triassic rift cluster (Şengör and Natal'in, 2001) may be subdivided into an eastern and a western domain: The domains are separated in the south by the North Kazakhstan Tectonic Units in which no significant effect of the Triassic extension is seen. The western domain stretches along the boundary between the Ural and the combined Tien Shan-South Kazakhstan and Central-North Kazakhstan domains of the Altaids. In this domain the Triassic grabens form a left-stepping *en échelon* array the formation of which may be explained by right-lateral shear, which is also seen along the Irtysh Keirogen (Allen et al., 1995, 2006).

The Triassic extensional (transtensional?) episode in the West Siberian Basin was short-lived and stretching was not the cause of the subsequent evolution of the basin. In the Koltogor-Urengoi Graben, for example, only Upper Triassic – Middle Jurassic sediments display increased thicknesses compared with the surrounding regions. Upper Jurassic Bazhenov deep-water oil shales have uniform thickness and facies in most parts of the basin (Kontorovich et al., 1975; Ulmishek, 2003, especially figs. 7 and 13). Cooling of the mantle since the late Permian extension caused a subsidence embracing a much wider region in a bovine-head pattern (cf. McKenzie, 1978) than the locally extended area in the Koltogor-Urengoi Graben. Within this regime, the Nadym Basin persisted as the deepest part of the basin for a long time. Neocomian prograding deltas from the east and west met each other in it.

Eastern Part. In the western half of the Altaids, their orogenic shaping came to an end essentially in the Permian, although, especially along its southern fringe (present geographical orientation), very considerable intracontinental shortening occurred during the Mesozoic and Cainozoic rejuvenating large mountains such as the Tien Shan Range (e.g. Burtman et al., 1996; Chen et al., 1992; Thompson et al, 2002: see Fig. 18). Only along the southernmost Tien-Shan, there was remnant subduction that reached into the Triassic. In the east, the Khangai-Khantey Ocean remained completely open after the Permian, although it had accumulated a considerable subduction-accretion prism a large portion of which had been invaded by magmatic fronts throughout the Palaeozoic, much like the present-day Japan, as Şengör et al. (1993) and Şengör and Natal'in (1996) had argued and since Van der Voo et al. (1999 and in press) corroborated. Şengör and Atayman (2009) argued however, that the opening allowed by Şengör et al. (1993) and their followers was not sufficient to bring the geology and the palaeomagnetic data completely into accord with one another. They instead suggested that the two arms of the Tuva-Mongol Arc Massif must be opened so that they would form almost a straight line even in the Permian (Fig. 18). For geologists familiar with the local geology this interpretation might seem unreasonable because, first, the youngest rocks in the main part of the Khangai-Khantey Accretionary Complex (43.2) are Carboniferous and the Triassic flysch is known only in its extreme northeastern part and, secondly, the accretionary complex in the central and western parts is intruded by late Palaeozoic plutons. However, on both flanks of the Tuva-Mongol Arc Massif east of about 105°E facing the Khangai-Khantey Ocean, arc-type magmatism lasted until the late Jurassic suggesting Mesozoic subduction in the Khangai-Khantey Ocean (see Fig. 18b for the late Permian situation).

Moreover, the internal structure of the Khangai-Khantey Unit is characterized by a haphazard geometry of subunits consisting of rocks of different ages (Fig. 1). In places, early Palaeozoic fault-bounded blocks occur among those belonging to medial to late Palaeozoic. One would think that these relationships contradict the idea of a continuous accretion as postulated by Şengör et al. (1993), Şengör and Natal'in (1996), Van der Voo et al. (1999, in press) and Şengör and Atayman (2009).

The deformation of the Khangai-Khantey Accretionary Complex caused by the closure of the Khangai-Khantey Ocean can be compared with the deformation of a plastic wedge extruded

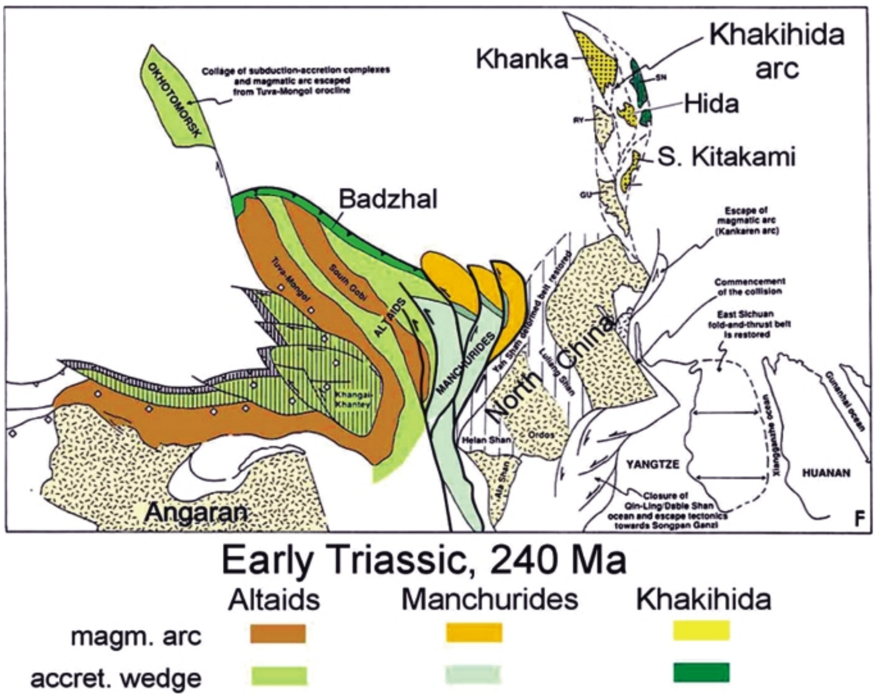

FIGURE 19: A possible reconstruction of the palaeotectonics of the eastern half of the Altaids during the early Triassic. Modified from Şengör and Natal'in (1996).

in a closing Prandtl cell as illustrated in Figs. 19–21; cf. Nádai, 1931, pp. 230ff.; Kanizay, 1962; Varns, 1962; see also Cummings, 1976; Şengör, 1979). The disruption of the primary age zonation within the Khangai-Khantey Accretionary Complex is thus explained as a result of the displacement along the slip-lines in the Prandtl cell. The arc massif orocline is pinched in the east which means that we can expect a considerable of extrusion of the Khangai-Khantey Accretionary Complex to the east. In fact, Bindeman et al. (2002) thought they could identify parts of not only the accretionary complex of the Khangai-Khantey accretionary complex to the east, in Kamchatka, but even parts of the inner Precambrian parts of the Tuva-Mongol Arc Massif. Van der Voo et al. (1999 and in press) were able to identify what they considered remnants of Mesozoic slabs subducted in the Khangai-Khantey Ocean under the northern parts of Siberia.

Another region of Mesozoic tectonic escape is the eastern end of the Altaids and the Manchurides (Natal'in 1991, 1993; Natal'in and Borukayev, 1991). This region Şengör and Natal'in (1996) already discussed under Nipponides.

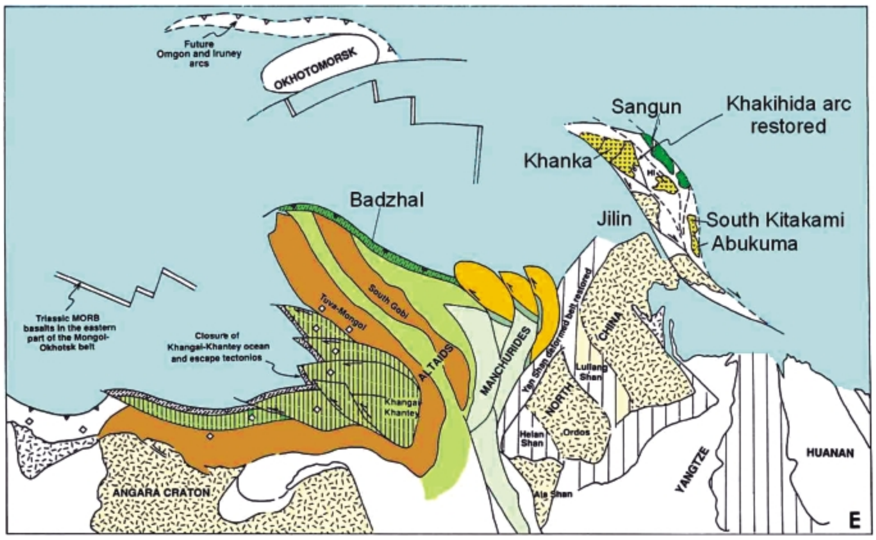

Figure 20: A possible reconstruction of the palaeotectonics of the eastern half of the Altaids during the late Triassic. Modified from Şengör and Natal'in (1996).

4.15 Further aspects of the Altaid development during the Mesozoic and the Cainozoic

After the closure of the Khangai-Khantey Ocean, the deformation of the Altaids did not stop; in fact it continues to this day. However, after the early Cretaceous, the Altaids were no longer the lords of their own destiny. Their further deformation was largely accomplished by the subduction, but mainly the collision events along the Tethysides to their south. Fig. 22 shows the areas affected by both Cimmeride (i. e., products of the closure of the Palaeo-Tethys and her dependencies such as the Banggong Co-Nu Jiang Marginal Basin System: see Şengör, 1984, 1987; Şengör et al., 1988; Şengör and Natal'in, 1996) and the Alpide (i. e., products of the closure of the Neo-Tethys: Şengör, 1984, 1987; Şengör et al., 1988; Şengör and Natal'in, 1996) orogenic systems that together constitute the Tethysides. Notice in this figure that the Altaids are located entirely within the Germanotype, i.e., blocky, non-penetrative, deformation area of both the Cimmerides and the Alpides. In these regions the typical structures are large ramp-valley basins, such as those of Turfan, Junggar and Alakol, rifts, the most famous of which is probably that of Lake Baykal, large strike-slip faults such as those of the Talasso-Fergana or Bolnai, and recompressed rifts, such as those of Hantay-Rybninsk or Irkineev (Fig. 22). Also, large basement uplifts similar to the US Rockies characterise especially the southern fringe of the Altaids, the most majestic of which is no doubt the Tien Shan. Some of the large basins that formed as parts of the post-Altaid development in Asia house a very large portion of the world's hydrocarbon reserves. Their Altaid basement has played a key role in determining the tectonic nature of these sediment receptacles.

5. Discussion

5.1 Crustal growth.

Şengör et al. (1993) have suggested that almost half of the Altaid accretionary complexes may be derived from material that is juvenile. This suggestion has since received strong support from geochemical studies conducted in various parts of the Altaid accretonary complexes and the arc magmatic systems localised not only within them, but even on the older Precambrian crust (e. g., Jahn et al., 2000a, b, c; Jahn, 2004). Heinhorst et al. (2000) also noticed that in much of central Kazakhstan, most calc-alkalic and sub-alkalic, high-K felsic rocks with a wide range of silica content have positive initial εNd values ranging from 0 (no growth) to +5.5 (considerable growth) and depleted mantle model ages in the range of 500–800 Ma. They contend that this ubiquitous, relatively young mantle extraction age is likely to characterize the lower crust of Central Kazakhstan. They view the basement here as back-arc oceanic crust that formed behind oceanwards drifting continental-margin slivers (i.e. the Kipchak Arc) during the initial stages of the active continental margin evolution of the Late Precambrian Russia/Siberia combined continent. They envisage the subsequet evolution as crustal transformation into the present lower crust during the Palaeozoic Altaid orogenic evolution, in which the back-arc crust was supposedly buried by magmatic arc and sedimentary material and recurrently affected by high-grade metamorphism, basaltic melt injection/underplating, and granitic melt extraction.

We agree with their conclusions, but think that they could have expressed the tectonic evolution in a more uniformitarian and therefore more testable manner had they used the model proposed by Şengör et al. (1993) and Şengör and Natal'in (1996). They point out that what they call 'anorogenic rift-related Permian peralkaline riebeckite granites with REE–Zr–Nb mineralization' also have very high positive εNd of +5 to +8. This is corroborated by Hong et al. 's (2004) observations in the same area also farther south.

Farther to the east, in the Altay *sensu lato* (the Lake Zone), Yarmolyuk et al. (2011) also found that many of the early Palaeozoic rocks had oceanic origins some 570 to 470 Ma ago. Their conclusions are supported by the earlier observations by Hoeck et al. (1999) who could find in the area they studied, in the Valley of the Lakes, no Precambrian intrusions; only early Palaeozoic intrusions, remobilised by Permian tectonism. In a more restricted area, in northern Xinjiang, Tang et al. (2010), have found evidence that the Baogutu adakitic rocks in the western Junggar area probably originated from about 95% of altered oceanic crust-derived magma and only 5% sediment-derived melt.

In Mongolia, the only juvenile addition to the crust is expected in the Khangai-Khantey Accretionary Complex, or in the accretionary complexes along the southern margin of the arc massif as the rest of the country consists of old Precambrian crust, similar to the Siberian Craton. Indeed, Jargalan and Fujimaki (1999) found, for example, that the Tsagaan Tsahir Uul granitic body in the Khangai-Khantey Unit was generated by slab melting in a subduction zone in the early Cambrian. But not all igneous rocks in Mongolia are juvenile. Budnikov et al. (1999) found, for example, the largest granitic batholith in Mongolia, the Hangay body, has entirely negative εNd signatures varying from -1.6 to -3.8, which is hardly surprising given the Precambrian age (including both Archaean and Proterozoic rocks) of its country rock.

The general conclusions of the current state of knowledge within the Altaids is that possibly somewhat more than half of their accretionary complexes are of juvenile, i. e., Ediacaran to Palaeozoc material. This is considerable as it amounts to no less than about 5 million km^2 of new crust. Given that it was generated in an interval of 350 Ma, it means some 0.5 km^3 of juvenile continental crust of 35 km thickness was generated every year during the Altaid evolution. This is about one third of the annual addition of continental crust to the earth. When one thinks of other Palaeozoic orogens in the world, this is most reasonable. The Altaids therefore did not add an unusual amount of crust to the planet, although they added a very substantial amount. As pointed out in Part I (Şengör et al., 2014), some authors confuse a high rate of crustal production with a prodigious amount of crustal production.

5.2 Global sea-level changes and the Altaid evolution

Fig. 23 shows the most recent estimates of global sea-level kindly provided by Professor Bilal Haq (written communication, 6th September, 2014; also see Haq and Al-Qahtani, 2005; Haq and Schutter, 2008; Haq et al., 1987, and Haq, 2014).This figure shows that global sea-level is mainly dominated by widespread rifting and collision events. Only in the late Carboniferous and the early Permian, there is a significant rise in global sea-level despite the widespread collision and following intracontinental shortening events accompanying the building-up of Pangaea. There are two possible candidates to cause this rise: the rifting of Greenland away from Norway along a line of stretching that extended into the present-day North Sea and the North German Basin plus the beginning rifting along the future Neo-Tethys (cf. Şengör and Atayman, 2009) and the maximum growth of the Altaid accretionary complexes. Fig. 24 shows how the growth of subduction accretion complexes helps to raise sea-level. When they are growing, subduction-accretion complexes steal volume from the oceans. This diminishes the volume of the oceans and raises sea-level. When collisions shorten and thicken the accretionary complexes, a part of the stolen volume is returned to the ocean basins and

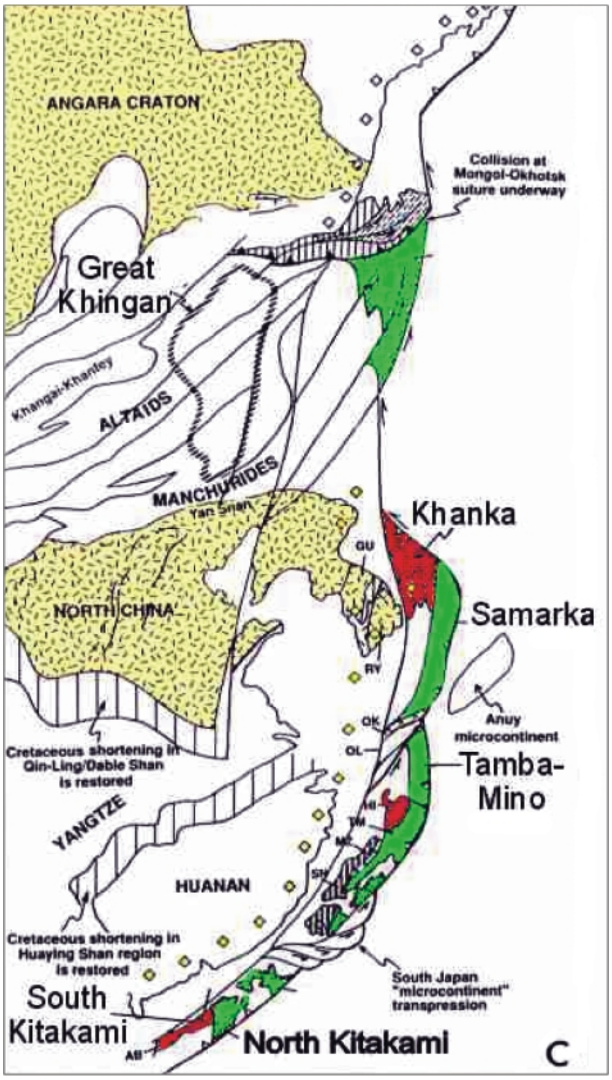

Figure 21: A possible reconstruction of the palaeotectonics of the eastern half of the Altaids during the late Jurassic-early Cretaceous. Modified from Şengör and Natal'in (1996).

sea level drops (Şengör, 2006).

But the Altaid evolution should have had another global effect in part tied to sea-level drop. As seen in Fig. 24, while subduction is going on CO_2 is continuously released to the atmosphere by volcanoes. This raises global atmospheric temperatures. When collision occurs and the flysch-rich subduction-accretion complexes rise above sea-level, their weathering begins sucking CO_2 from the atmosphere. Because the collision also turns off subduction-related vulcanicity, the CO_2 content of the atmosphere drops and global temperatures fall. Thus we should have seen atmospheric chilling following the medial Permian in the Altaids (Şengör, 2006). But exactly the opposite is seen: the Gondwanian glaciation that raged during the late Carboniferous-earliest Permian had vanished after the Asselian. Neither there was a serious sea-level rise to ameliorate the global climate. Quite the contrary: sea-level continued drop-

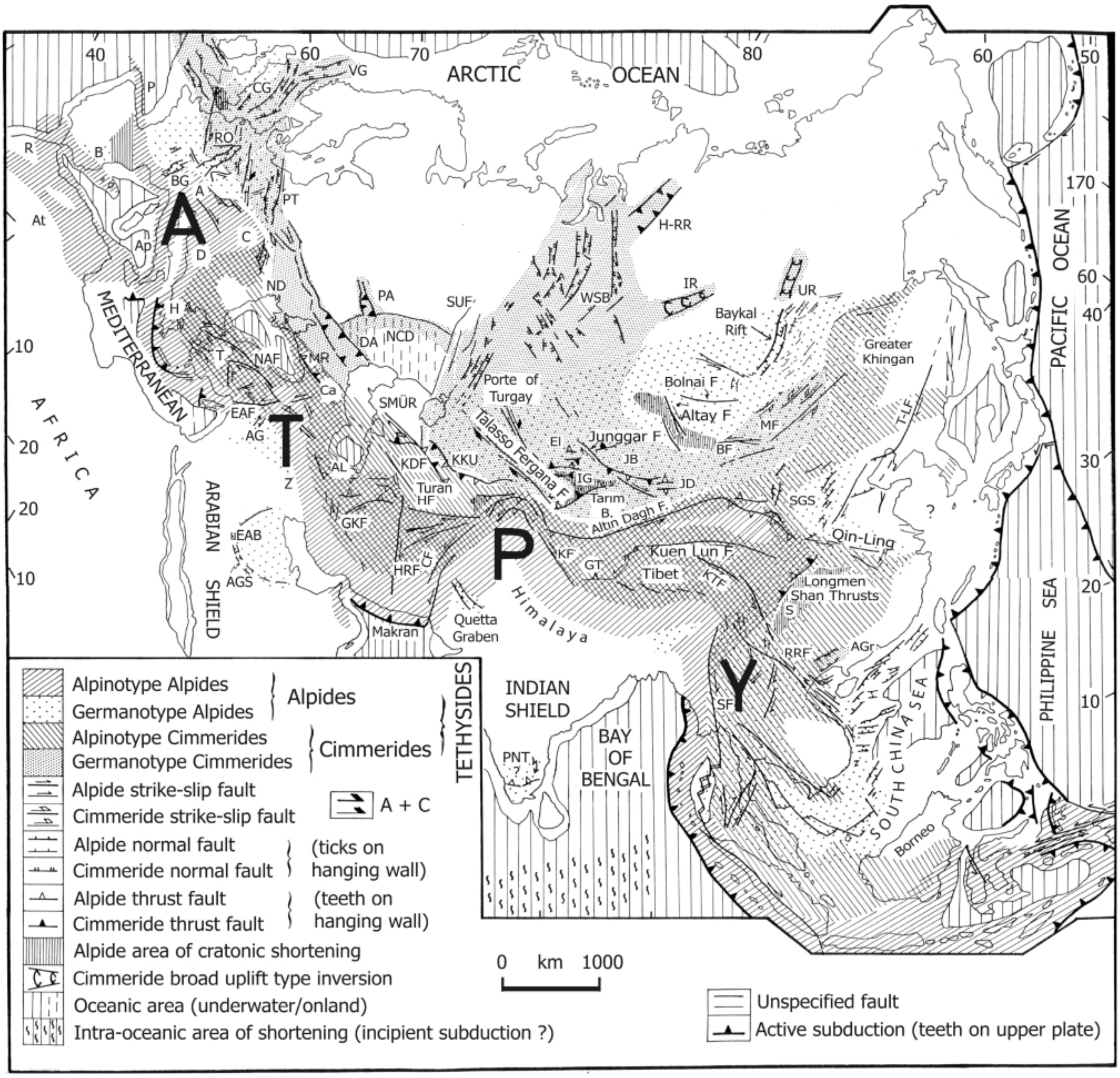

FIGURE 22: Fore- and hinterland deformation areas of the Tethysides (modified from Şengör et al., 1988). The hinterland deformation in Asia very lagerly deformed the Altaid edifice and is continuing to do so. Note that both the Germanotype Cimmerides and the Germanotype Alpides avoid the Siberian Craton. Key to lettering: Large letters: A. Alpine Syntaxis, T. Turkish Syntaxis, P. Pamir Syntexis, Y. Yunnan Syntaxis. Smaller letters: A. Alps, AG. Akçakale Rift, AGr. An Chau Rift, Al. Alborz Mountains, Ap. Apennines, At. Atlas Mountains (sensu lato), B. Betic Cordillera, BF. Bogdo Fault, BG. Bresse Rift, C. Carpathians, Ca. Caucasus (sensu lato), CAGS. Central Arabian Graben System, CF. Chaman Fault, CG. Central Graben, D. Dinarides, DA. Dnyepr-Donetz Aulacogen, EAB. East Arabian Block, EAF. East Anatolian Fault, EI. East Ili Basin, GKF. Great Kavir Fault, GT. Geerze Thrust, H. Hellenides, HF. Herat Fault, HRF. Harirud Fault, H-RR. Hantay-Rybninsk Rift, IG. Issyk Gol Intramontane Basin, IR. Irkineev Rift, KDF. Kopet Dagh Fault, KF. Karakorum Fault, KKU. Kizil Kum Uplift, KTF. Kang Ting Fault, MF. Mongolian faults, MR. Main Range of the Greater Caucasus, NAF. North Anatolian Fault, NCD. North Caspian Depression, PA. Pachelma Aulacogen, PNT. Palni-Nilgiri Hills Thrust, PT. Polish Trough, SGS. Shanxi Rift System, BMUR. South Mangyshlat-Ust Yurt Ridge, SUF. South Uralian faults, T. Turkish ranges, TD. Turfan depression, T-LF. Tan-Lu Fault, UR. Ura Rift, VG. Viking Graben, WSB. West Siberian Basin, Z. Zagrides.

ping, despite the Altaid delay. One wonders whether it was the increasing aridity and not so much the atmospheric temperature that spelled the death sentence of the Gondwanian continental glaciers or whether there was increased Permian

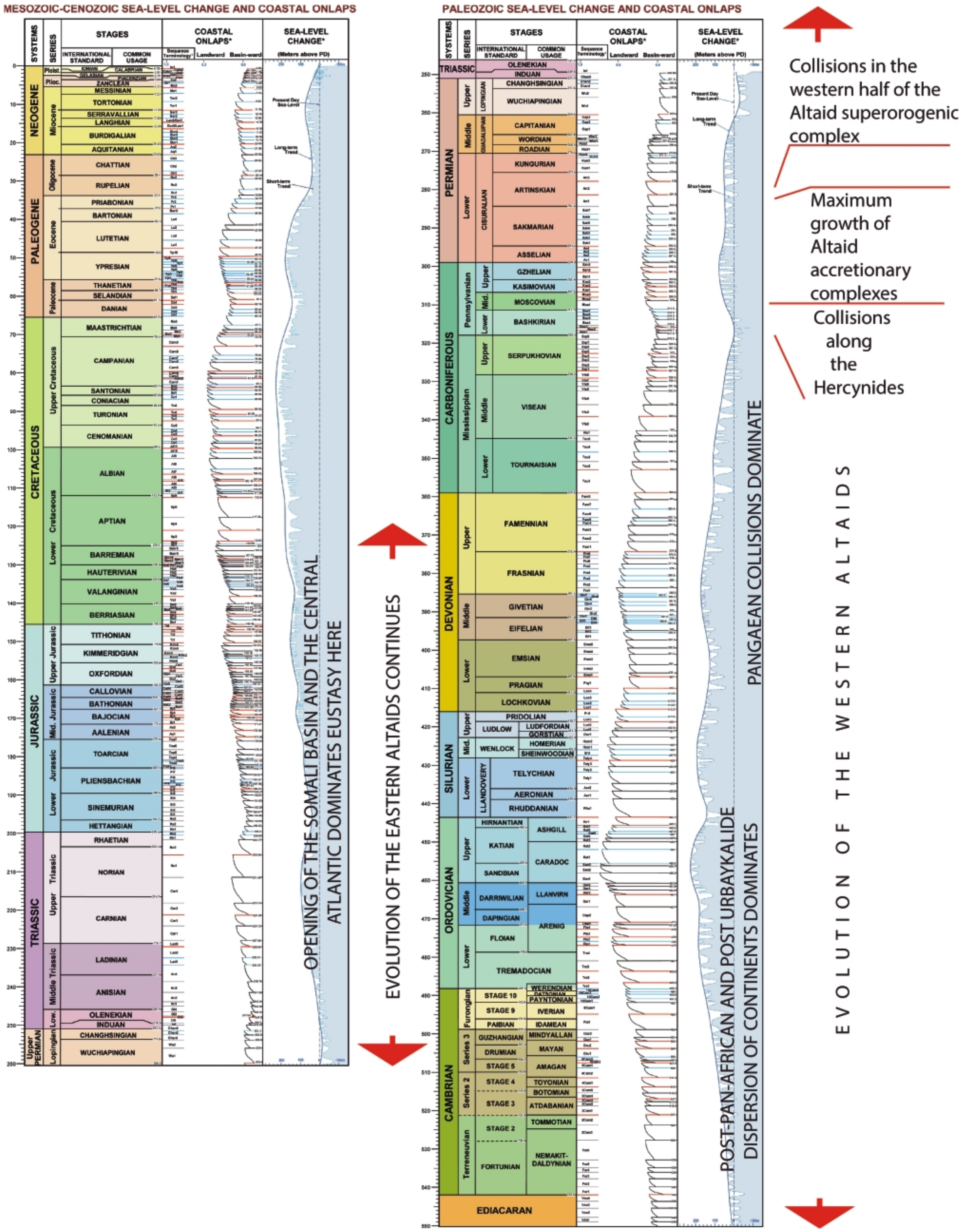

Figure 23: World-wide eustatic sea-level changes (Professor Bilal Haq, written communication 6th September 2014) plotted against some of the tectonic events in the world to show their possible genetic relationships. Notice that the late Carboniferous-Permian higher-than-expected sea level coincides in time with the widest development of the Altaid accretionary complexes.

vulcanicity along the circum-Gondwanian subduction zones releasing more CO_2 to the atmosphere than before. In any case, Gondwanian glaciation and global tectonics relationships still hide a major secret waiting to be unearthed unless the relative sizes of the accretionary complexes of Altaids were very much different from what our reconstructions imply.

5.3 Use of palaeomagnetic observations in large terrains with diffuse deformation

In complexly and diffusely deformed areas it is of importance to know whether the deformation affecting the sampled areas is confined to narrow shear zones or represent strain in a much wider area. This difference is of importance in controlling the rate and amount of rotations around vertical axes.

6. Conclusions

Palaeomagnetic data collected during the last decade of the twentieth and the first decade-and-a-half of the twenty-first century are shown to be compatible with the operation of only two arc systems throughout the evolution of the Altaids in Central and Northwestern Asia from the latest Neoproterozoic (Ediacaran) to the early Cretaceous, namely the Kipchak and the Tuva-Mongol arcs. Throughout this period there is no record of any collision, be it between major continents, be it between individual arc fragments or small continental slivers within the Altaids until they were 'sealed' during the late Palaeozoic by the collision with them of what Şengör and Natal'in called the 'Intermediate Units' of Asia, namely the Tarim Fragment and North China carrying the Manchurides and the arc systems that connected the two (Şengör and Natal'in, 1996). They in part grew on the ruins of an older, collisional orogenic system,

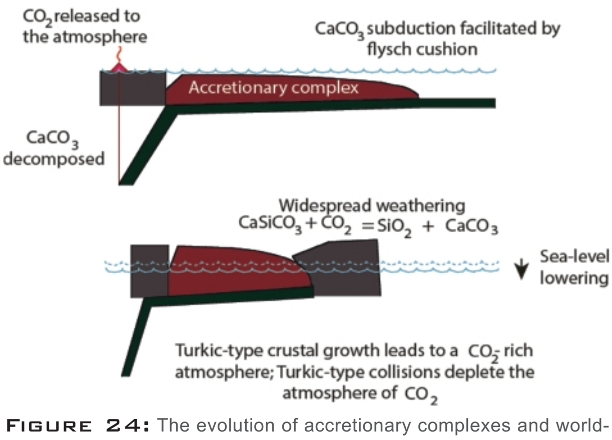

Figure 24: The evolution of accretionary complexes and world-wide sea-level. In the upper figure, no collision has yet occurred and the accretionary complexes are wide and low (most accretionary complexes are today underwater except one of the largest, that of Makran). While the accretionary complex is growing, subduction is going on, sea-level is pushed up (if the accretionary complex growth is the only factor controlling it) and the volcanoes pump CO_2 into the atmosphere. These are ideal conditions for a greenhouse world. In the lower figure, collision already occurred, the accretionary complex is shortened, thickened and surfaced, sea-level dropped and the CO_2 supply to the atmosphere stopped because the subduction-related volcanoes died. In addition, because of the weathering of the calc-silicates (Urey reaction) CO_2 is sucked from the atmosphere. All these create ideal conditions of an icehouse world.

the Urbaykalides. Conflating the two would be like claiming that the Hercynides and the Alpides are the same orogenic belt. Using other appellations than Altaids for the orogenic system described in this paper would not only violate the rules of priority (Eduard Suess has the priority), but also be wholly inconsistent with their unity of structure and evolution.

Following the terminal Palaeozoic collision, the Khangai-Khantey Ocean began closing between the two flanks of the Tuva-Mongol Arc Massif. That closure finally ended in the Cretaceous, although marine conditions had long retired from the top of the accretionary complexes making up the Khangai-Khantey Unit since the Triassic. This was somewhat similar to the prevailing terrestrial, even desert conditions atop the Makran subduction-accretion complex north of the Arabian Sea which is still being subducted under it.

During the Mesozoic and the Cainozoic the Altaid edifice continued to undergo deformations, but mostly generating non-penetrative, blocky 'Germanotype' structures under the influence first of the Cimmerides and then the Alpides to their south.

During the Altaid evolution, on average some 0.5 km^3 continental crust formed every year which is roughly 1/3 of the global average. More crust formed in the western part than in the eastern part, although this may be an artefact of preservation, i. e., of the escape of much of the Khangai-Khantey Subduction-Accretion Complex east- and northeastward. Although this means that the Altaids added some 3 million km^2 to the continental crust, the rate at which this happened was nothing out of the ordinary. The Altaids were indeed a factory of continental crust, but one which worked at usual rates. Some have criticised this statement by saying that there was no unusual crustal growth during the Altaid evolution. Since no claim had ever been made for unusual rates of generation of the continental crust, these criticisms were made against phantom assertions.

The available palaeomagnetic data were an immense help in constraining the tectonic evolution of the Altaids and testing the Şengör et al. (1993) model, but the employment of these observations also showed how woefully inadequate they are and this is for two reasons: one is that the number of observations are as yet very few and wholly inadequate to be able to generate a unique solution. Also, the structural environment (not only the structure of the outcrop at the site of observation) in which the observations were made are almost never reported. Without knowing the structural picture in a fairly large area (10,000 km^2 minimum) around the observation spot at scales of 1/25,000, 1/100,000 and 1/250,000, no palaeomagnetic observation can be evaluated with full satisfaction. It is of extreme importance that the palaeomagnetician works with a structural geologist familiar with such a large area in which the observations are to be made and that the observation sites be decided jointly.

A similar problem exists in geochemistry and isotope geology. Much sample grabbing has taken place in the Altaids without adequately learning the geology of the region. Consequently, the results, although most welcome additions to our knowledge, cannot be adequately assessed in terms of the entire evolution of the orogenic system (cf. Şengör et al., 2014; Şengör, 2014).

The Altaid research has greatly suffered from fashion addiction. There was a deplorable multiplication of mute 'terranes' in numerous publications or an uncalled-for frenzy of age dating with highly sophisticated methods without looking at the geology properly. Particularly, what is now most needed is careful field mapping combined with age dating and palaeomagnetic observations and extensive palaeontology. Funding agencies ought to desist from funding research without a solid field basis.

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