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Paleomagnetism of mid-Paleozoic subduction-related volcanics from the Chingiz Range in NE Kazakhstan: The evolving paleogeography of the amalgamating Eurasian composite continent

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ABSTRACT

The tectonic and paleogeographic evolution of the Ural-Mongol belt between the cratons of Baltica, Siberia, and Tarim is key to the formation of the Eurasian composite continent during Paleozoic time, but the views on this complicated process remain disparate and sometimes controversial. A study of three volcanic formations of mid-Silurian, Lower to Middle Devonian, and Middle Devonian age from the southwestern boundary of the Chingiz Range (NE Kazakhstan) yields what are interpreted as primary paleomagnetic directions that help clarify the evolution of the belt. A single-polarity characteristic component in mid-Silurian andesites yields a positive intraformational conglomerate test, whereas dual-polarity prefolding components are isolated from the two Devonian collections. Post-folding, reversed-polarity overprint directions have also been isolated and are likely of Permo-Triassic age. These new data can be evaluated together with previously published paleomagnetic results from Paleozoic rocks in the Chingiz Range, and allow us to establish with confidence the polarity of each result, and hence to determine the hemisphere in which the area was located at a given time. We conclude that NE Kazakhstan was steadily moving northward, albeit with variable velocity, crossing the equator in Silurian time. These new paleomagnetic data from the Chingiz Range also agree with and reinforce the hypothesis that the strongly curved volcanic belts of Kazakhstan underwent oroclinal bending between Middle Devonian and Middle Permian time. A comparison of the Chingiz paleolatitudes with those of Siberia shows, insofar as the sparse data allow, similarities between the northward motion of the Chingiz unit and that of Siberia, which imposes important constraints on the evolving paleogeography of the Ural-Mongol belt.

Keywords: paleomagnetism, volcanic arc, orocline, Middle Paleozoic, Central Asia, Siberia, paleogeography.

INTRODUCTION

Palinspastic reconstructions at various scales are a concise way to illustrate the paleogeographic and tectonic evolution of an area, and a certain degree of consistency between reconstructions proposed by different researchers can be expected, provided that the extent of our knowledge is adequate. Unfortunately, this is not the situation for the Ural-Mongol mobile belt in Eurasia (Fig. 1), for which the published reconstructions are highly controversial and even mutually exclusive (see, for example, Mossakovsky et al., 1993; Didenko et al., 1994; Filippova et al., 2001; Şengör and Natal'in, 1996; Yakubchuk et al., 2001, 2002; Stampfli and Borel, 2002; Puchkov, 1997, 2000). If one examines the different reconstructions of the Ural-Mongol mobile belt components, it would be difficult indeed (i.e., without carefully studying the figure captions), to understand that it is the same area that is being illustrated. Names and component descriptions of the belt change from one publication to the other, whereas the spatial relationships between mobile zones and older Precambrian cratons range in distance over an order of magnitude or more. Different reconstructions may reveal relative orientations varying by more than 100°. Thus, one can find a slowly evolving flotilla of small fragments (Mossakovsky et al., 1993; Didenko et al., 1994; Filippova et al., 2001), or a gradually coiling serpentine island arc (Şengör and Natal'in, 1996; Yakubchuk et al., 2001, 2002), or an array of larger blocks that consume surrounding oceans according to rules that change from author to author (Stampfli and Borel, 2002; Puchkov, 1997, 2000). The coexistence of so many dissimilar models strongly indicates that we lack even first-order knowledge about the paleogeography and kinematics of the Ural-Mongol mobile belt constituents. Major cratons like Baltica, Siberia, and Tarim are often the only recognizable features in these reconstructions, and even their positions may be quite dissimilar—see the discussion in Cocks and Torsvik (2007) about the Siberian late Paleozoic paleopoles.

It seems to us that this lack of consensus, which contrasts markedly with the much less varying syntheses of Alpine or circum-Iapetus belts, can be attributed to two main reasons. One is that the Paleozoic motions of Siberia, Tarim, Amuria (Mongolia, Amuria [a part of the Mongol-Okhotsk suture]; e.g., Kravchinsky et al., 2002a), and the China blocks are very incompletely known. The other is that the numbers as well as the quality of the available paleomagnetic data have been grossly inadequate.

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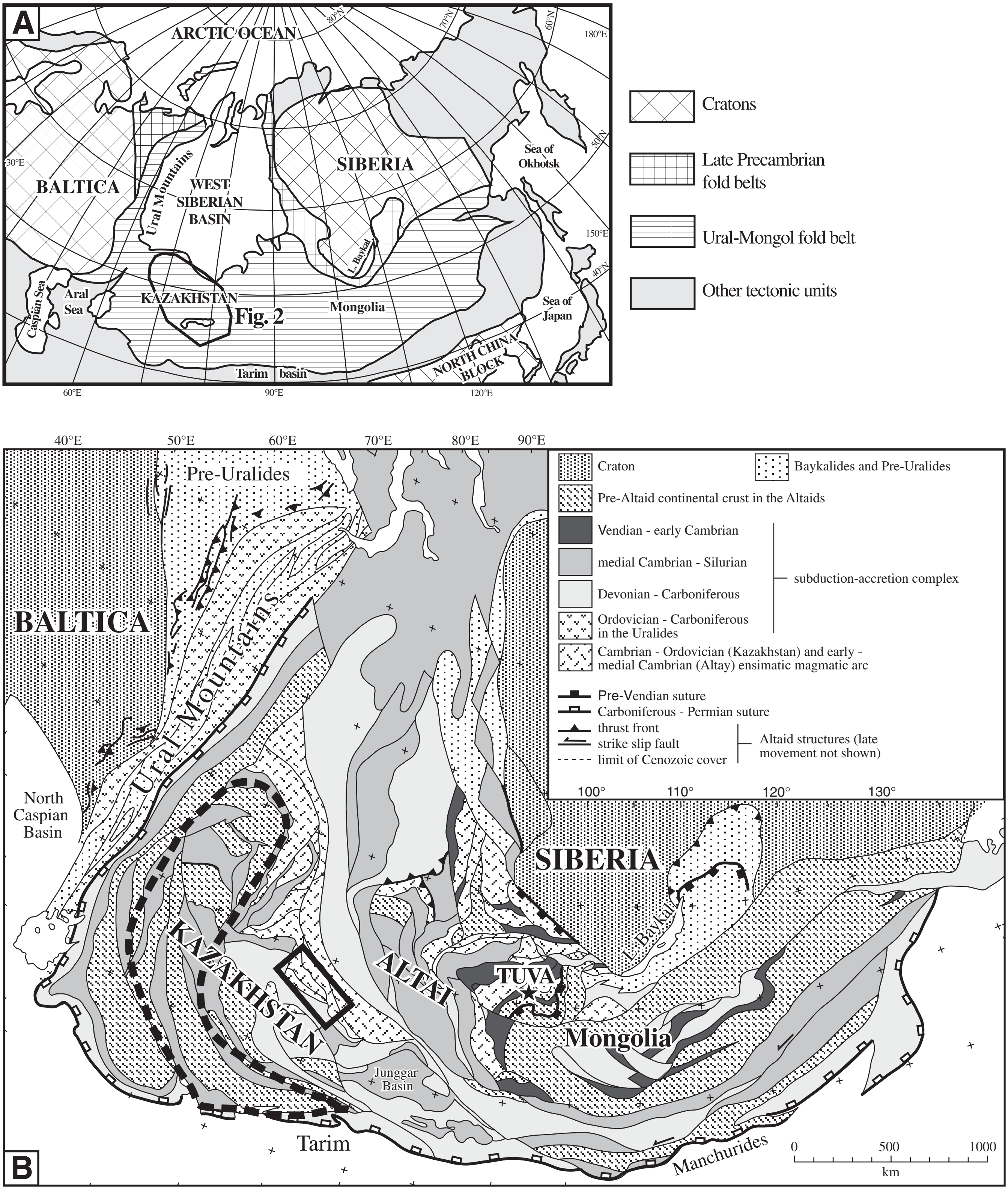

Figure 1. (A) Location of the Ural-Mongol fold belt within Eurasia. (B) Generalized tectonic map of the Ural-Mongol belts (the Altaids) and major surrounding units (modified from Fig. 21.18 of Şengör and Natal'in (1996). The rectangle outlines the Chingiz block. Thick dashed line denotes the boundaries of the Kokchetav–North Tien Shan domain (KNTD) as defined by Levashova et al. (2007). The star denotes the location of the field area (Tuva) of Bachtadse et al. (2000), where Upper Silurian–Lower Devonian rocks were sampled.

The Ural-Mongol mobile belt stretches for nearly 10,000 km from the Arctic Ocean along the Ural Mountains between Europe and Asia and then onward through Central Asia almost to the Pacific (Fig. 1A). Its western part, the Urals (Fig. 1B), displays long narrow sets of folded and imbricated thrusts (Puchkov, 1997, 2000) and is generally akin to other orogenic belts resulting from continent-continent collisions, such as the Caledonides and Appalachians. In contrast, the central parts of the Ural-Mongol mobile belt, including Kazakhstan, the Altai, and northwestern Mongolia, have a mosaic structure with no prevailing structural trend (Fig. 1B).

In Kazakhstan the Ural-Mongol mobile belt reaches its maximum width and is likely to be at its most complex. The early Paleozoic structure comprises tectonically juxtaposed microcontinents with Precambrian basement, early Paleozoic subduction-related volcanic complexes, and accretionary wedges or flysch sequences. In contrast, the middle to late Paleozoic geology is dominated by a pair of strongly curved volcanic belts (Fig. 2), which are unconformably superposed on older structures. The outer belt comprises volcano-sedimentary Upper Silurian rocks and thick sequences of Lower to Middle Devonian subduction-related extrusives. In the Frasnian, volcanic activity shifted to a more interior belt, ~150 km to the south, and continued there in the Famennian-Tournaisian. Farther inward displacement of volcanic activity occurred in the Early Carboniferous and lasted until the Middle Permian. The composition of the volcanic series strongly varies within each belt but generally progresses from basalt to andesite and/or dacite and then to rhyolite (Tectonics of Kazakhstan, 1982). After the Late Silurian, and up to the Early Permian, the volcanics are of calc-alkaline affinity and are considered to be of subduction-related origin (Kurchavov, 1994; Tevelev, 2001). Volcanic activity lasted for ca. 150 Ma, while

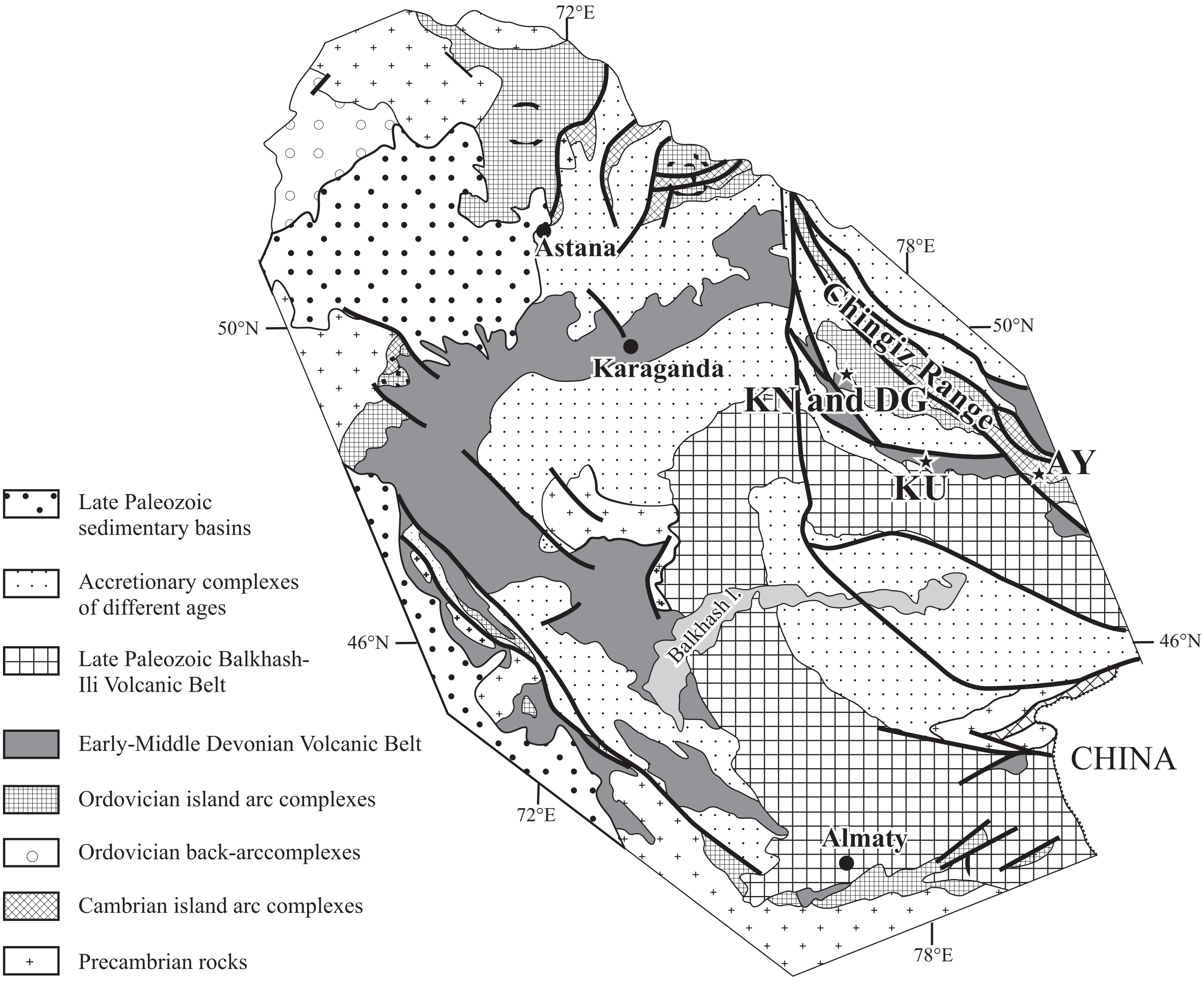

Figure 2. Schematic map of major rock complexes in Kazakhstan, simplified after Degtyarev (2003), with main faults shown as thick solid lines. Stars are the study areas labeled as described in the text. Abbreviations: AY—Ayaguz; KN and DG—Kaynar-Dogolan; KU—Kurbakanas.

terrigenous sedimentation continued more and more to the interior side of the looplike belts. As a result, Late Devonian to late Paleozoic volcanics overlie Silurian and Early Devonian flysch series and accretionary wedges.

To remedy the scarcity of paleomagnetic data, we have initiated a program in the past seven years to obtain temporal sequences of paleomagnetic results for a significant time interval for key tectonic units of Kazakhstan's Ural-Mongol mobile belt. This program is not yet completed, except for one major tectonic unit, which is the Kokchetav–North Tien Shan domain (Levashova et al., 2007). The Kokchetav–North Tien Shan domain stretches from north Tarim to almost the West Siberian Basin and is outlined by a thick dashed contour in Figure 1B. It comprises several Precambrian microcontinents and numerous remnants of early Paleozoic island arcs, marginal basins, and accretionary wedges. It is thought that in the Late Ordovician these units had amalgamated into a contiguous domain (Levashova et al., 2007). Nine paleomagnetic results from the Kokchetav–North Tien Shan domain have been combined to show its latitudinal motion from the Late Ordovician until the Late Permian; the data support the concept of a more or less coherent motion of the Kokchetav–North Tien Shan domain and Baltica (Levashova et al., 2007), and imply that Baltica and the Kokchetav–North Tien Shan domain were never very far apart after the Silurian.

A similar program (Collins et al., 2003; Levashova et al., 2003a, 2003b) was started in the Chingiz Range, which stretches for more than 600 km in northeast Kazakhstan (Fig. 2). These reports noted acceptable, albeit temporally incomplete, agreement of the observed paleolatitudes with the Siberian reference values for the early Paleozoic, followed by a disparity in the middle Paleozoic. Although the possibility of coherent motion of the Chingiz arc and the Siberian craton was discussed in these papers (Collins et al., 2003; Levashova et al., 2003a), a conclusion remained rather elusive due to large time gaps between the results, poor quality of the Devonian data (Levashova et al., 2003a), and the lack of reliable middle and late Paleozoic poles for the Siberian plate, except for the ca. 360 Ma pole of Kravchinsky et al. (2002b). To fill the gap in temporal coverage in NE Kazakhstan, we present here three new paleomagnetic results from Middle Silurian and Lower to Middle Devonian rocks of the Chingiz area and compare these with the available data from SW Kazakhstan, Kyrgyzstan, Siberia, and Baltica. This will allow us to determine the paleolatitudinal movements of the tectonic units in this area and to place constraints on the tectonic evolution of the Ural-Mongol mobile belt.

GEOLOGICAL SETTING AND SAMPLING

The Chingiz Range sensu stricto is a tectonic unit that extends for ~600 km in a NW-SE direction in northeastern Kazakhstan (Fig. 2). It contains Cambrian to Early Silurian volcanic series of island-arc affinity (Degtyarev, 1999), some of which were studied by us earlier (Collins et al., 2003; Levashova et al., 2003a). No accretionary complexes of Cambrian or Tremadocian age are known in this area. In contrast, Arenigian to Late Ordovician accretionary complexes and Middle Ordovician to Early Silurian flysch sequences are widespread and become progressively younger from the northeast to the southwest. After the Middle Ordovician, the ages of volcanic series also show a younging trend from NE toward the SW.

The lower Paleozoic rocks of the Chingiz unit do not contain continent-derived sediments, so that it is regarded as an intraoceanic arc (Degtyarev, 1999). Most authors agree that subduction under the Chingiz island arc was from the southwest to the northeast (in present-day coordinates) since the Middle Ordovician. Recently, detailed mapping coupled with new age determinations and restoration of displacements along the abundant strike-slip faults provided evidence that the polarity of the arc has remained the same since the Cambrian (Degtyarev and Tolmacheva, 2005), although other authors earlier hypothesized a reversal of subduction in the Early Ordovician (Samygin, 1974; Zonenshain et al., 1990). By the end of Early Silurian time, volcanism diminished in the Chingiz Range; the overlying Upper Silurian redbeds only locally and rarely contain lava flows or tuffaceous members. In a few places, these redbeds reside on older rocks with a pronounced angular unconformity, although elsewhere this unconformity is absent (Degtyarev and Ryazantsev, 1993). These authors also note that the pattern of younger Devonian volcanism generally follows the spatial distribution of the Upper Silurian sediments.

In Early Devonian time, a renewed outburst of volcanism took place in many areas of Kazakhstan. The most active volcanism is confined to a relatively narrow horseshoe-shaped band (the Early-Middle Devonian volcanic belt in Fig. 2), which was recognized several decades ago (Bogdanov, 1965). Generally, this belt follows the boundary between the older ("Caledonian") structures outside of the horseshoe and the younger ("Variscan") fold belt inside it. In the Chingiz area sensu lato, this volcanism is of mid-Lochkovian age (Schegoleva et al., 1993) and is located generally to the SW of the early Paleozoic and Silurian island-arc complexes (Fig. 2). These Devonian volcanics of the northeastern arm of the belt partly overlap, and generally parallel the older Chingiz structures. Volcanic activity in this belt lasted until the Givetian, whereas Late Devonian and Tournaisian volcanics are scarce or absent altogether in this Range.

In the Visean, volcanism resumed and lasted until the Late Permian (Sal'menova and Koshkin, 1990); the resulting late Paleozoic volcanic belt (see Fig. 2) is called the Balkhash-Ili belt. Both the Devonian and the Balkhash-Ili belts are usually considered as Andean-type active margins with subduction under them directed away from the horseshoe interior; however, the views on the evolution of these belts, their strongly curved outlines in particular, are controversial (Kurchavov, 2001; Tevelev, 2001). Judging by numerous angular unconformities in the Chingiz island-arc sequence and adjacent parts of the volcanic belts, multiple late Paleozoic deformation events affected the area. For our purposes, we need to mention the post–Early Silurian, post-Givetian, Visean, and Late Permian events. As noted above, however, the magnitude of each deformation varies laterally, and the deformation pattern is not uniform (Degtyarev and Ryazantsev, 1993).

On the whole, the Chingiz island arc of intraoceanic setting was active for more than 100 million years (Degtyarev, 1999). The clear reduction in the volcanism during the later Silurian may indicate either greatly diminished subduction, or a major reorganization of the plate boundary system. Regardless, subduction-related volcanism resumed at the Andean-type active margin in Early Devonian time and lasted well into the Permian (Tevelev, 2001, and references therein).

Our study concentrated on mid-Silurian volcanic rocks of the Chingiz island arc and Devonian rocks of the Devonian volcanic belt from the southwestern part of the Chingiz area. Brief descriptions follow, using the two-letter abbreviations that we use to identify the sampling areas (see labels in Fig. 2).

Locality AY (Ayaguz; 48.0°N, 80.7°E)

Marine sediments are covered by andesite flows at this section. The youngest fossiliferous sediments, of late Wenlockian–early Ludlovian age, occur below the base of the volcanic pile; therefore, we can consider the volcanic rocks as of Ludlovian age. We sampled 12 lava flows with clear flow contacts in a SE-dipping monocline; the total true thickness studied is more than 200 m. Bedding attitudes were measured on several sedimentary layers intercalated with the volcanics. Also sampled were 20 lava cobbles from two conglomerate members between lava flows. We should add that, except for one strongly weathered flow, we studied all cooling units at this section, and no other Silurian volcanics are present within a reasonable distance from it.

Localities KN and DG (Kaynar-Dogolan; 49.5°N, 77.0°E)

Lower to lower Middle Devonian volcanics and tuffs of basaltic to rhyolitic composition were sampled from a bowl-like syncline and from three adjacent but separate monoclines with different attitudes up to 15 km apart. Lava flows and tuffs were sampled at 44 sites. Bedding attitudes could usually be measured on stratified tuffs and sediments, although occasionally bedding had to be obtained from flow contacts.

Locality KU (Kurbakanas; 48.3°N, 78.3°E)

Givetian basalts with sparse interbeds of sediments occupy a large area but, due to low relief, are rather poorly exposed. Earlier, Levashova et al. (2003a) studied five flow units (sites) from a section distributed about a single sedimentary layer. We revisited this area and sampled 13 more sites from basaltic flows with varying attitudes. All sampled sites are within 20 m from sedimentary layers.

METHODS

Generally, a set of samples collected from a separate cooling unit was called a site, wherever practical in terms of numbers and spatial distribution. Paleomagnetic samples were collected either as fist-sized blocks oriented with a magnetic compass, or were drilled with a portable drill and oriented with a magnetic or sun compass. Our convention is to label a site using the letters and numbers of its first sample but with a capital letter at the beginning; for instance, site N3814 contains samples n3814 through n3819, followed by site N3820, and so forth.

Cubic specimens of 8 cm^3 volume were sawed from hand blocks; cores were sliced into 22-mm-long cylinders. The collection was studied in the paleomagnetic laboratories of the Geological Institute of the Russian Academy of Sciences in Moscow and of the University of Michigan in Ann Arbor. In Moscow, specimens were heated in a homemade oven with internal residual fields of ~10 nT and measured with a JR-4 spinner magnetometer with a noise level of 0.05 mA/m. In Ann Arbor, specimens were stepwise demagnetized utilizing an Analytical Services TD-48 thermal demagnetizer with internal residual fields of <10 nT; magnetizations were measured with a 2G Enterprises cryogenic magnetometer in a magnetically shielded room. In both laboratories, the specimens were stepwise demagnetized in 15–20 increments up to 680 °C. No systematic difference was found between the samples that were treated in Moscow or Ann Arbor, and the data have been pooled.

Demagnetization results were plotted in orthogonal vector diagrams (Zijderveld, 1967). Visually identified linear trajectories were used to determine directions of magnetic components by principal component analysis (PCA), employing a least-squares fit comprising three or more demagnetization steps (Kirschvink, 1980), anchoring the fitting lines to the origin where appropriate.

If complete component separation is not achieved during demagnetization, the common practice is to combine the PCA-calculated sample directions (Kirschvink, 1980) and remagnetization circles employing the technique of McFadden and McElhinny (1988). When this was the case, remagnetization circles were combined with direct observations for computing site-means of both lower- and higher-temperature components. This approach, however, is not omnipotent. For instance, if only remagnetization circles are available at a given site and, as is often the case, these circles converge at acute angles, their intersection gives a biased estimate of the least-dispersed component (Schmidt, 1985). In other sites where one can determine only component directions that form a strongly elongate distribution, a calculation of a mean direction is undesirable. In such cases, one can calculate the site-mean great circle in the first site, and the best-fitting plane in the second. For calculation of the overall mean for a formation, such great circles can be combined with "standard" site-mean directions (McFadden and McElhinny, 1988). All statistics below are calculated for 95% confidence level. Paleomagnetic software written by Jean-Pascal Cogné (2003), Randy Enkin (http://gsc.nrcan.gc.ca/dir/index_e.php?id = 12377), and Stanislav V. Shipunov was used in the analysis.

RESULTS

Mid-Silurian Volcanics (Locality AY)

In the dark-colored volcanics, a weak unstable component is completely removed by 350–400 °C, and a well-defined characteristic remanent magnetization (ChRM) that shows rectilinear decay to the origin can be isolated (Figs. 3A and 3C). In contrast, the natural remanent magnetization (NRM) of brick-red varieties is strongly dominated by an overprint; nevertheless, a ChRM could reliably be isolated from most of these samples as well (Fig. 3B). All in all, every one of the 12 sites and all but six of the 83 samples gave useful results. ChRM site-mean directions are rather well clustered, and the overall mean direction is well defined (GSA Data Repository Table DR1[1]). Judging by unblocking temperatures, this remanence resides in both magnetite and hematite in varying proportion, both "magnetite" and "hematite" components being directionally identical (Figs. 3A and 3C). Bedding attitudes at this section show minor variation, and, although maximum grouping occurs at 100% unfolding, the fold test (McElhinny, 1964) is inconclusive, as the observed concentration parameter ratio of 1.27 is less than the critical value of F-statistics of 2.05 (Table DR1 [see footnote 1]; Figs. 4A and 4B).

Thirteen cobbles out of 20 that were sampled from two beds of intraformational conglomerate show demagnetization patterns that are very similar to those in the host rocks (Fig. 3D). In six samples, however, the "magnetite" component clearly misses the origin, whereas the "hematite" ChRM decays to it (Fig. 3E). For all ChRMs from 19 cobbles, the normalized vector-resultant of 0.165 is much less than the critical value of 0.367 (Mardia, 1972); hence the conglomerate test is positive (Fig. 4C), and the ChRM in Silurian volcanics can be deemed primary. The "magnetite" intermediate component in the six samples is very scattered also.

In most cases, ChRM site-mean directions from adjacent sites are statistically different. This means that no serial correlation of site-mean directions is present in this data set, and each site-mean can be regarded as an independent spot-reading of the field. The distribution of site-mean virtual geomagnetic poles has a standard angular deviation (S) of 12.3º, which agrees well with the value of ~12.5º for the geomagnetic field near the equator during the past 5 Ma (Merrill et al., 1996). This finding as well as the presence of sedimentary members among the volcanics, indicates that accumulation of the volcanic pile lasted long enough to average secular variation adequately. Hence we conclude that the ChRM in the studied section is likely to be primary, and that its mean direction originally did correspond to that of the ancient field.

Lower to Lower Middle Devonian Rocks of KN and DG Localities

A low-temperature component, which clusters around the present-day field before tilt correction, is usually removed below 200–250°. Only at one site (P254) did a similar remanence

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[1] GSA Data Repository Item 2008170, four tables of site-mean directions of paleomagnetic components and related statistical parameters, is available at www.geosociety.org/pubs/ft2008.htm. Requests may also be sent to editing@geosociety.org.

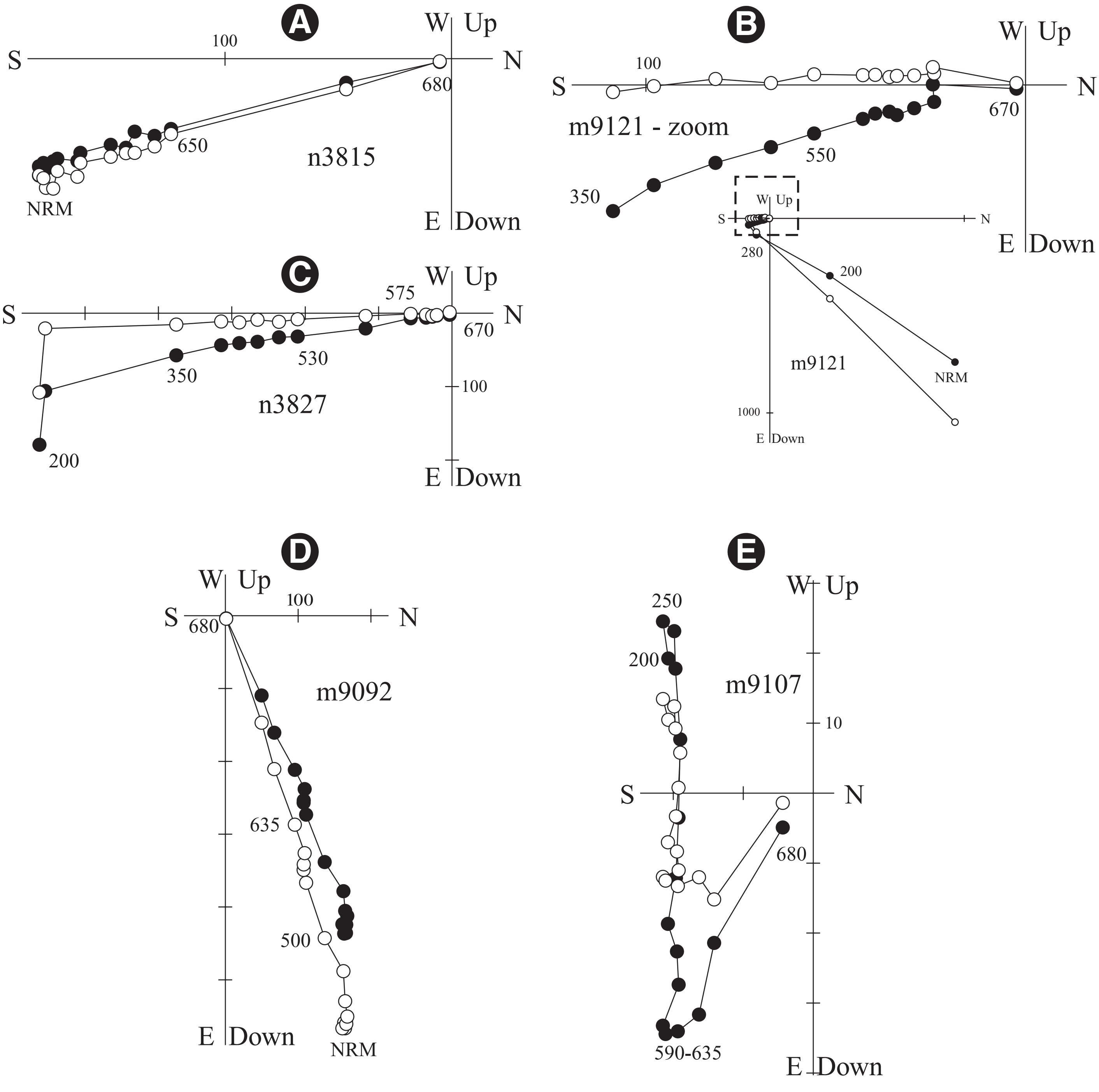

Figure 3. Representative thermal demagnetization plots of Silurian rocks from locality AY (Ayaguz), in stratigraphic coordinates: (A)–(C) andesite flows; (D) and (E) cobbles from an intraformational conglomerate. Filled (open) circles represent vector endpoints projected onto the horizontal (vertical) plane. Temperature steps are in degrees Celsius. Magnetization intensities are in mA/m. For clarity, natural remanent magnetization (NRM) points are omitted from some plots.

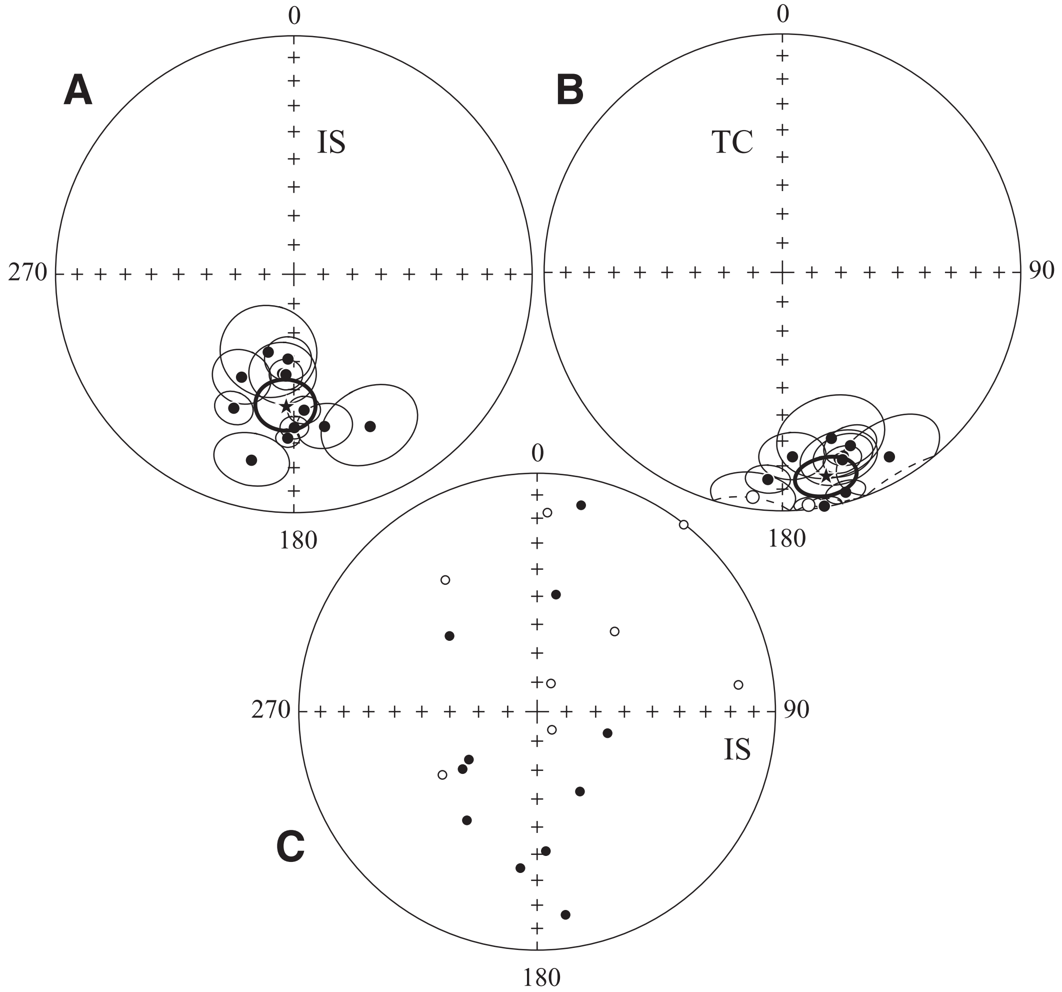

Figure 4. Stereoplots of site-mean directions of the high-temperature components (HTC) with associated confidence circles (thin lines) of Silurian volcanic rocks from locality AY (Ayaguz), (A) in situ (IS) and (B) after tilt correction (TC). Star with associated confidence circle (thick line) is the overall mean directions of the characteristic remanence. (C) HTC directions from cobbles from an intraformational conglomerate. Filled (open) symbols and solid (dashed) lines are projected onto the lower (upper) hemisphere.

persist over the entire heating range (not shown), suggesting that this is a chemical remanence due to recent weathering.

After removal of the low-temperature remanence, many sites had stable components, but not all. A few sites yielded what only can be called anomalous mean directions, and eight gave very scattered and inconsistent results. In total, we had to reject ten sites. In 28 of the remaining 34 sites, an upward-pointing component A was often isolated (Figs. 5A and 5C–5E). This intermediate-temperature component may decay to the origin (Fig. 5A) or can miss it (Figs. 5C–5F); even in the former case, however, vector endpoints often shift along a great-circle path at intermediate and high temperatures (Fig. 5B). This component is typically isolated below 570 °C suggesting magnetite as the main carrier, but the corresponding linear segments on orthogonal plots sometimes extend into the hematite range (Fig. 5C).

The exclusively reversed-polarity component A is moderately to well grouped at most sites (Table DR2; see footnote 1). Its site-mean directions show a rather diffuse distribution with similar dispersions in situ and after tilt correction (Table DR2; Figs. 6A and 6B), but a distinct maximum at 35% is observed during stepwise untilting (Fig. 6C). The maximum concentration parameter, k, of 16 differs significantly from the tilt-corrected value (8) but not from the in situ value. Judging by demagnetization characteristics and the result of the fold test, this reversed component A is an overprint that was acquired during a late stage of deformation. Geological data, however, clearly indicate that Lower to lower Middle Devonian volcanics were deformed in the Givetian but were also affected by folding in the late Paleozoic. Therefore, it is more accurate to state that component A was acquired not during a single folding event but at the final stages of deformation in this area.

The presence of another component (labeled B) is clearly indicated in many samples, and this component B is always characterized by the highest unblocking temperatures for a given sample and by a rather different direction from that of component A. However, proper isolation of component B was prevented in several samples by the acquisition of spurious remanence at high temperatures (Fig. 5C). Component B has negative inclinations at six sites (Figs. 5F and 6D–6E) and is of opposite polarity at 12 others (Figs. 5D and 6D–6E). Component-B site-means are rather scattered, but they clearly form two nearly antipodal clusters, in particular after tilt correction (Figs. 6D–6E). The two polarity-means differ by 175.2º (4.8º), which is less than the critical angle γ_c of 17.4º (McFadden and McElhinny, 1990), rendering the reversal test positive (Table DR3; see footnote 1). This remanence shows a twofold increase in grouping upon tilt correction (Table DR3), which is statistically significant, and renders the fold test (McElhinny, 1964) positive as well.

The mean component B direction ends up with acceptable statistical parameters and is confirmed by positive fold and reversal tests (Table DR3; Figs. 6D–6E), despite some anomalous and inconsistently scattered sites. Also heartening is the gross similarity of this result with the KU one (discussed next).

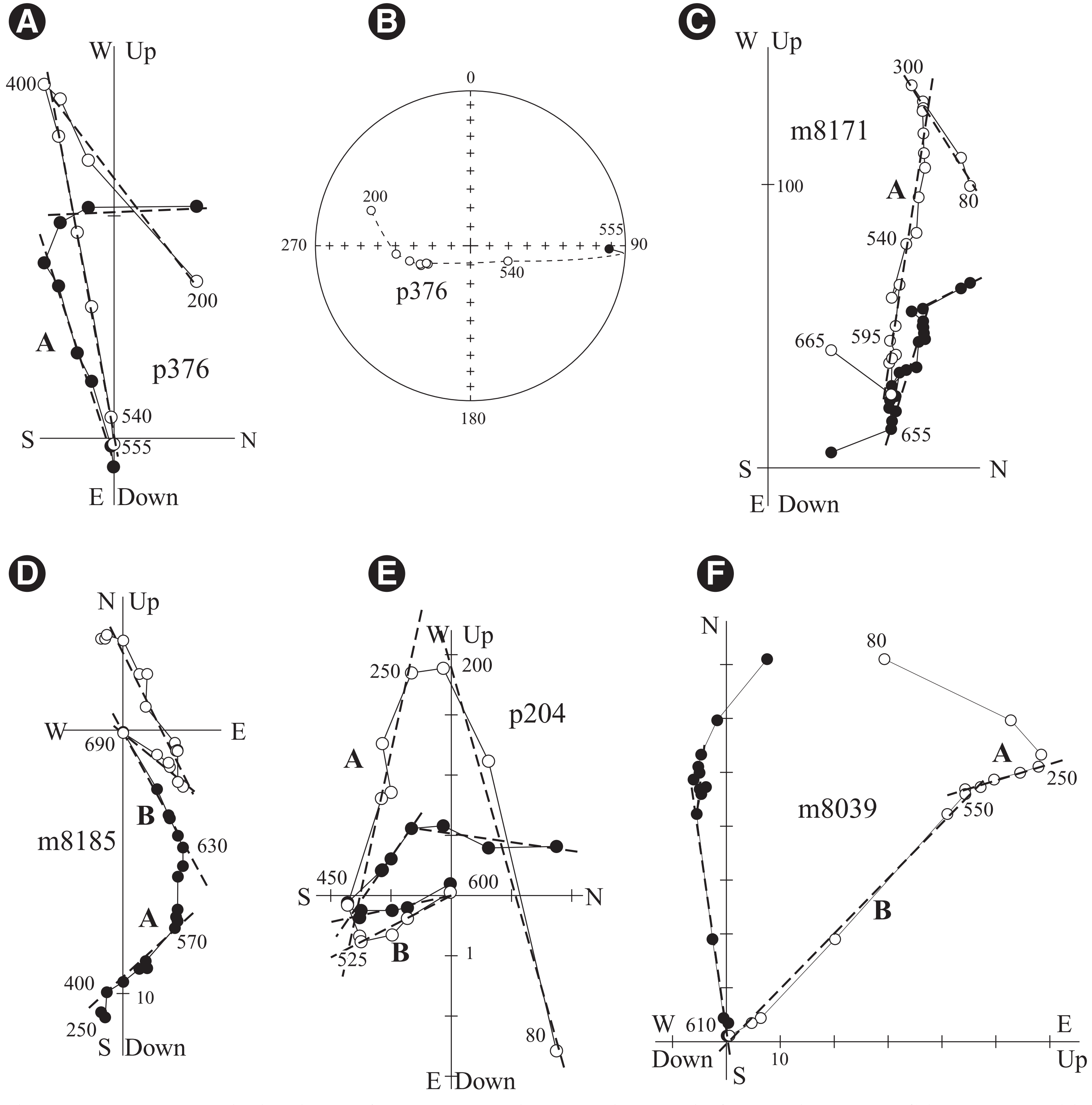

Figure 5. Thermal demagnetization diagrams from the Lower–Middle Devonian volcanics from locality KN and DG (Kaynar-Dogolan) in geographic coordinates. For clarity, natural remanent magnetization (NRM) points are omitted from the plots. Thick dashed lines denote identified and labeled (A and B) components (see Tables DR2 and DR3). Other notation for demagnetization plots and stereonet as in Figures 3 and 4.

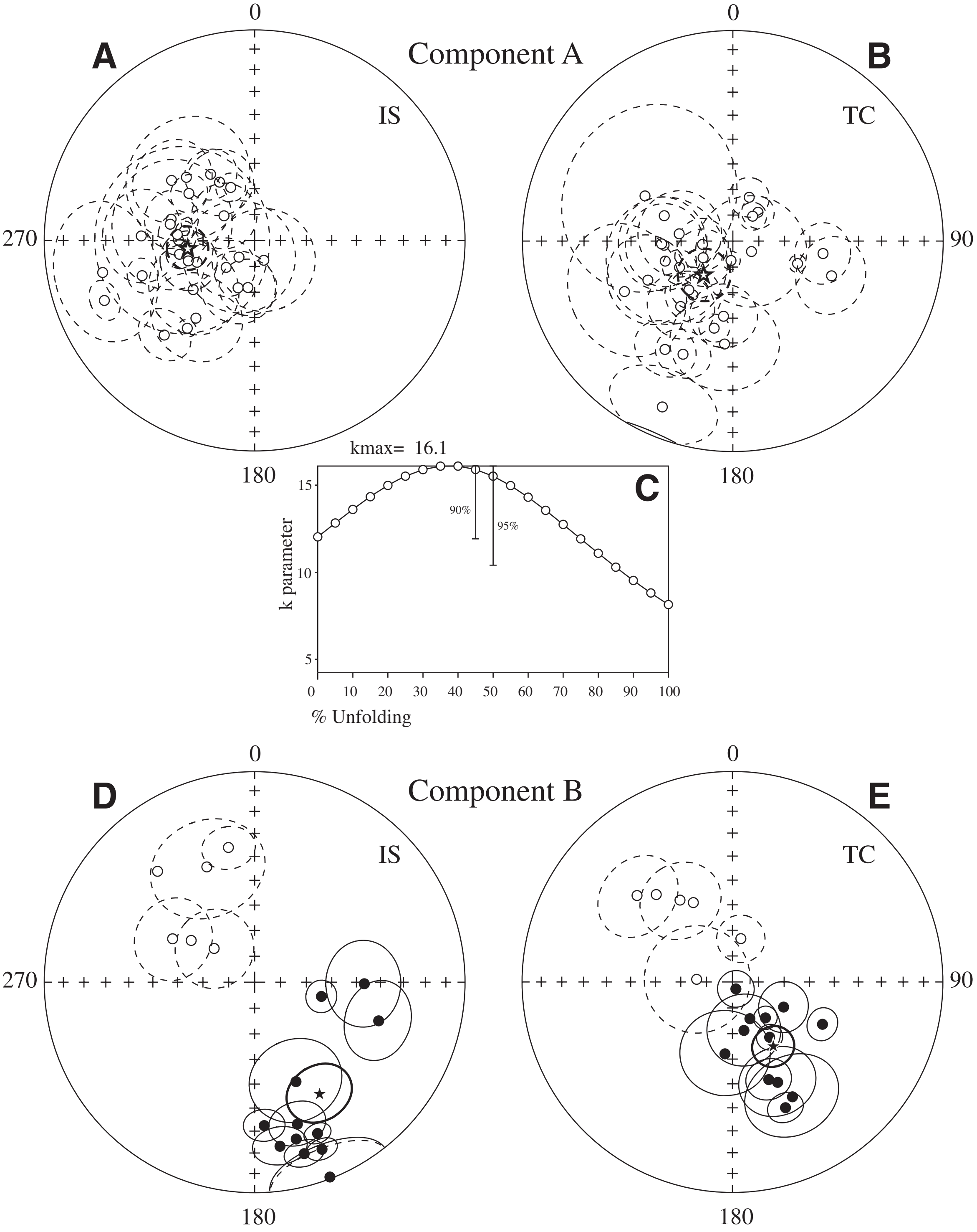

Figure 6. Stereoplots showing site-mean directions of components A and B isolated from Lower to lower Middle Devonian rocks at locality KN and DG (Kaynar-Dogolan), (A) and (D) in situ and (B) and (E) after tilt correction, and (C) a plot of concentration parameter versus percent unfolding for component-A data. Stars are the overall mean directions of the corresponding components with associated confidence circles (thick lines). Mean directions without confidence circles are shown when two samples are used at a site. Other notation as in Figure 4.

Givetian Basalts (Locality KU)

Low-temperature component directions cluster around the present-day field before tilt correction, and were usually removed below 200–250 °C. At higher temperatures, two components (A and B) were isolated from most samples.

Component A persists from ~250 °C until above 500° and is sometimes the only component present in a sample (Fig. 7A). In other samples, this remanence does not decay to the origin and is succeeded by another component (B). This can be seen as sequential rectilinear segments on orthogonal plots (Figs. 7B–7D) or in remagnetization circles in stereonets when the decay of component A produces a curved trajectory in the orthogonal demagnetization diagrams. Proper component separation may not always be reached in such a case, even if two apparently rectilinear segments seem evident. For instance, component B is unlikely to be fully and reliably isolated in sample n3863 (Fig. 7C). It can also happen that the intermediate-temperature (A) component is contaminated, as suggested by the diagram of sample m9202 (Fig. 7D). In this sample, overlapping of unblocking spectra of components A and B seems responsible. For several sites, remagnetization circles (Fig. 7E) had to be used, and for some six other sites we could not determine any well-clustered mean A, B, or anomalous direction with any confidence. These sites are, of course, not included in Table DR4 (see footnote 1).

Despite this occasional problematic aspect of the determination of component A or B directions, we feel confident that the site-mean directions and remagnetization circles of Table DR4 are well determined. We have combined our data with the previous results from five sites of the same formation at this locality (Levashova et al., 2003a). In this combined set, 12 site-mean directions of component A form a tight cluster in situ (Table DR4; Fig. 8A), excluding two anomalous outliers (not shown). A three-fold increase in dispersion upon tilt correction (Table DR4; Fig. 8B) indicates that component A is post-folding.

The combined component-B site-mean directions and remagnetization circle intersections form two groups on the stereonet (Figs. 8C and 8D): one with four site-means with north and up directions and another comprising four remagnetization circles and two site-means; the latter group defines a south and down cluster of directions. The corresponding polarity-means differ by 168.3° (11.7°), which is less than the critical angle γ_c of 15.3° (McFadden and McElhinny, 1990), rendering the reversal test positive (Table DR4; Figs. 8C and 8D). For the ten sites with B-directions, tilt-corrected data show a better grouping than in situ directions, but this is not statistically significant; also insignificant is a slight improvement in data grouping at 80% unfolding. With some reservation, we conclude that the dual-polarity component B is primary and of Middle Devonian age. This view is further supported by general agreement between the Early to early Middle Devonian KN and DG result and late Middle Devonian KU data (Table 1).

DISCUSSION

Overview of Results from the Chingiz Area Deemed of Primary Origin

Several studies reported Paleozoic paleomagnetic results from the Chingiz island arc and adjacent units and the nearby and younger complexes of the Devonian and late Paleozoic volcanic belts (Table 1).

Collins et al. (2003) reported paleomagnetic data from Upper Cambrian andesites and Lower Ordovician (Arenigian) redbeds from the central part of the Chingiz Range (results labeled CL and OE, respectively, in Table 1). The ancient nature of both magnetizations is confirmed by positive fold tests. There is a large scatter of Arenigian site-mean declinations, however, presumably because of local vertical-axis rotations. The statistical limits on the Early Ordovician mean inclination are therefore much tighter than those for the mean declination.

Lower Silurian volcanics (SI) were studied 30–40 km to the southwest from localities OE and CL. The primary origin of the dual-polarity magnetization in these Silurian rocks is confirmed by fold-, reversal-, and conglomerate tests (Levashova et al., 2003a). Our new Ludlovian AY result is also primary and reliable, as evidenced by adequate statistics and a positive conglomerate test.

A result from Lower to lower Middle Devonian volcanics (G1) and another one from Upper Silurian redbeds (G2) were reported by Grishin et al. (1997). Despite very limited statistics, the lack of the field tests and hence, rather low reliability (Table 1), these results are included in the analysis as “supporting” entries.

Burtman et al. (1998) studied Lower to lower Middle Devonian rocks and presented a mean direction based on principal component analysis, applied to stepwise demagnetization of 40 samples (out of 97 studied), of which 30 are reversed and ten are of normal polarity. Although the sample directions are rather scattered, the mean appears statistically well defined, but this is only because unit weight was given to samples and not to sites (B1, Table 1); even so, the k-value is only 12. However, the fold and reversal tests are reported as positive. The most disturbing feature is the simple observation that Burtman et al. (1998) sampled the same locality KN as we did. Thus, the difference in declinations cannot be attributed to local tectonics. The in situ data (in Fig. 4 of Burtman et al. [1998]) display a cluster centered on our overall A-direction. We assume, therefore, that the mean direction represents the same late Paleozoic remagnetization as our secondary component A. We assign the result of Burtman et al. (1998) Permian remagnetization status and exclude it from the discussion of Devonian paleogeography.

Upper Permian basalts from the southeastern part of the Chingiz Range are the youngest rocks that have been studied in the area. The Late Permian results (PA and PB, Table 1) are confirmed by a positive fold test and are reliable (Levashova et al., 2003b).

We consider these published and our new results together, resulting in a data set consisting of inclinations (paleolatitudes) as well as declinations from CL, SI, AY, KN and DG, KU, PA, and PB (Table 1), that can be used for tectonic analysis. The result from locality OE can be used for paleolatitude analysis only. Finally, we will see that the supporting role of the G1 and G2 results will strengthen rather than diminish the conclusions.

Overprint Data

The locality-mean directions of post-folding magnetizations in Silurian and Devonian rocks of localities KU (this study) and from SI and GV (Levashova et al., 2003a) agree in situ within the size of the symbols (Fig. 9, Table 2). The KN and DG secondary component A after 35% unfolding is in close agreement with these three remagnetization directions (Fig. 9), despite the distance of ~200 km between the localities. Judging by the very tight grouping of overprint directions over a large area, we suggest that remagnetization was contemporaneous and of regional extent.

While the exclusively reversed polarity could be taken to suggest a remagnetization event during the reversed Kiaman superchron (ca. 315–265 Ma) (Opdyke and Channell, 1996), the mean overprint inclination of –70.4° ± 1.9° is steeper by ~20° than the mean inclination of –49° ± 4° of the prefolding and presumably primary remanence in the Upper Permian basalts from the PA and PB localities (Table 1; Levashova et al., 2003b). Similar very steep overprint inclinations were also found in other parts of the Chingiz area (Collins et al., 2003). It seems highly unlikely that the primary magnetization at localities PA and PB, and the secondary magnetizations from the study area constitute an unbiased record

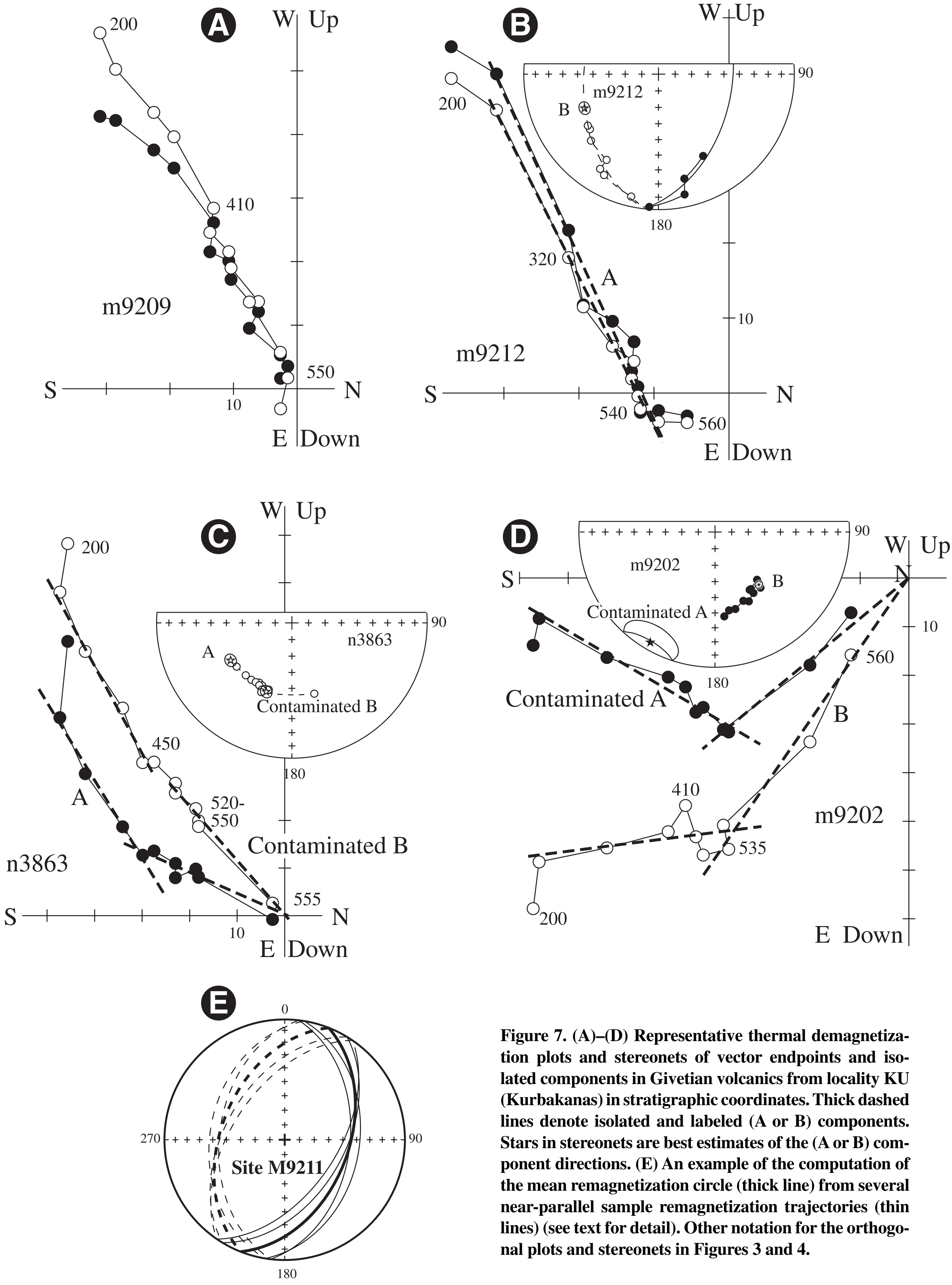

Figure 7. (A)–(D) Representative thermal demagnetization plots and stereonets of vector endpoints and isolated components in Givetian volcanics from locality KU (Kurbakanas) in stratigraphic coordinates. Thick dashed lines denote isolated and labeled (A or B) components. Stars in stereonets are best estimates of the (A or B) component directions. (E) An example of the computation of the mean remagnetization circle (thick line) from several near-parallel sample remagnetization trajectories (thin lines) (see text for detail). Other notation for the orthogonal plots and stereonets in Figures 3 and 4.

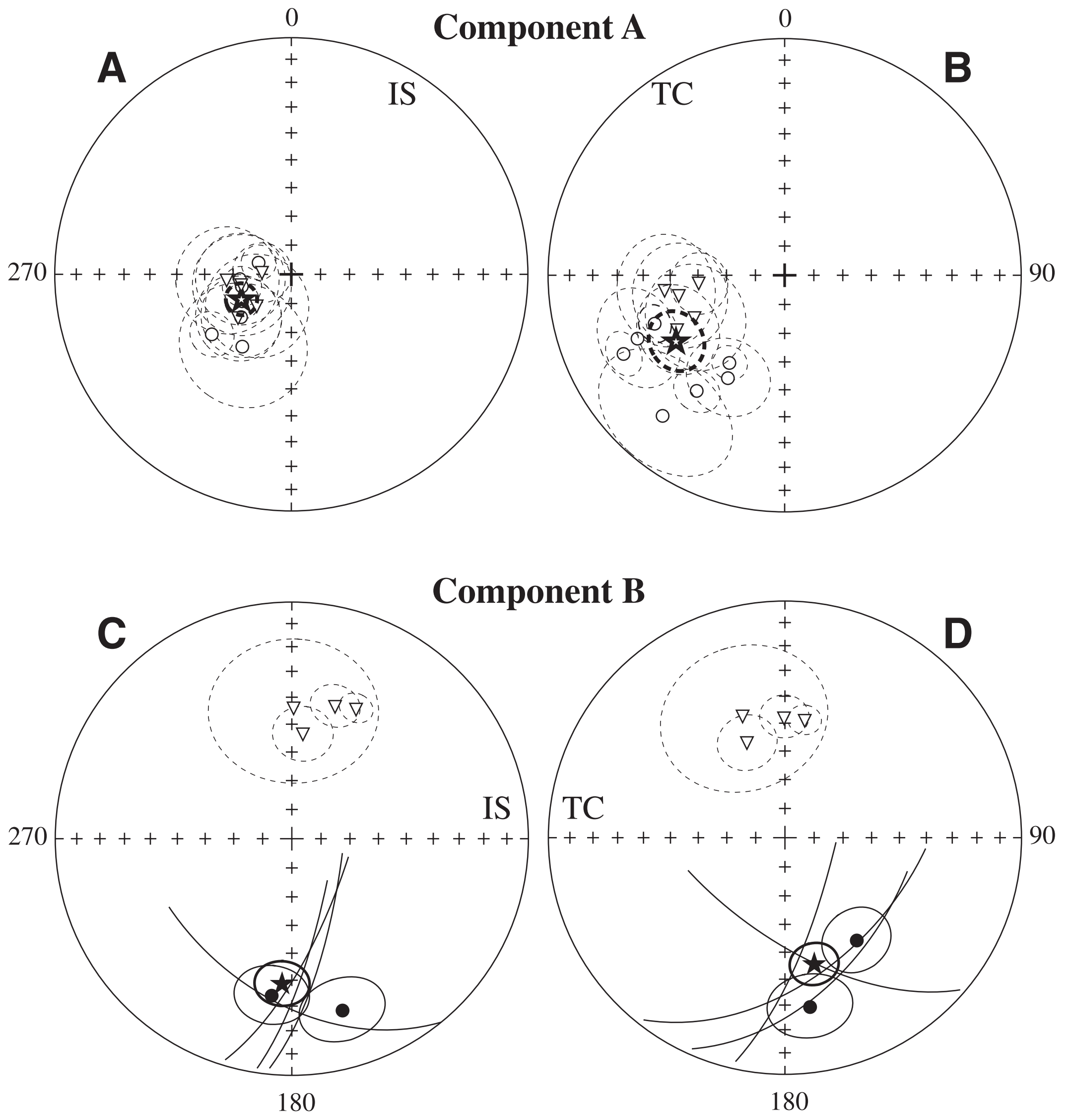

Figure 8. (A) and (B) Stereonets of component-A site-mean directions. Triangles are the results from Levashova et al. (2003a) and open circles from this study, with associated confidence circles (thin lines) from the Givetian volcanics of locality KU (Kurbakanas). (A) in situ and (B) after tilt correction. Star with associated confidence circle (thick line) is the locality-mean direction of the secondary component A. (C) and (D) Component-B site-mean directions, triangles and filled circles as in (A) and (B) with associated confidence circles in the Givetian volcanics from locality KU in situ (C) and after tilt correction (D). Star with associated confidence circle (thick line) is the locality-mean HTC direction.

TABLE 1. SUMMARY OF PRIMARY PALEOMAGNETIC RESULTS FROM NORTHEASTERN KAZAKHSTAN

Result	Age	Stat	Tests	D°	I°	k	α_{95}°	Plat °	REF
PA	P_l(260)	(8)	F	264.9	–50.2	107	4.8	+31 ± 4	1
PB	P_l(260)	(8)	F	237.0	–47.9	216	3.4	+30 ± 3	1
KU	D_m(388)	(10)	R	167.0	44.3	41	7.8	+26 ± 6	TP
B1[#]	$D_{e\text{-}m}$(402)	40(?)	FR	52	41	12	6.4	+24 ± 7	2
G1	$D_{e\text{-}m}$(402)	9(1)	NT	168	48	25	9.3	+29 ± 12	3
KN and DG	$D_{e\text{-}m}$(402)	(18)	FR	147.7	60.2	20	8.0	+41 ± 9	TP
G2	S_l(420)	12(2)	NT	144	11	-	13	+6 ± 7	3
AY	$S_{e\text{-}l}$(425)	(12)	C	168.0	13.2	28	8.4	+7 ± 4	TP
SI	S_e (433)	(12)	FCR	216.5	–2.8	12	13.3	–1 ± 4	4
OE[##]	O_e(480)	(11)	F	*146.3*	–23.1	10	14.8	–12 ± 4	5
CL	Cm_l(495)	(8)	F	109.1	–35.2	33	9.8	–19 ± 6	5

Note: Results are abbreviated as in the text. Age abbreviations: Cm—Cambrian; other period abbreviations are standard; subscripts e—early, m—middle, and l—late; ages in Ma are from Gradstein et al. (2004). Stat—statistical treatment: numbers without parentheses represent samples, when given unit weight by the authors, whereas numbers in parentheses represent the number of sites. Tests, positive field tests: F—fold test; R—reversal test; C—conglomerate test; NT—no tests. D—declination; I—inclination; k—concentration parameter; α95—radius of 95% confidence circle (Fisher, 1953) directions are presented in stratigraphic coordinates. Plat—paleolatitude, positive if in the Northern Hemisphere, with 95% confidence intervals. REF, reference: 1—Levashova et al. (2003b); 2—Burtman et al. (1998); 3—Grishin et al. (1997); 4—Levashova et al. (2003a); 5—Collins et al. (2003); TP—this paper. Note that the G2 result is based on remagnetization circles only, so that the concentration parameter cannot be computed.

[#] Excluded (see text for detail).

[##] The elongated distribution of site-mean directions renders the mean declination (in italics) imprecise.

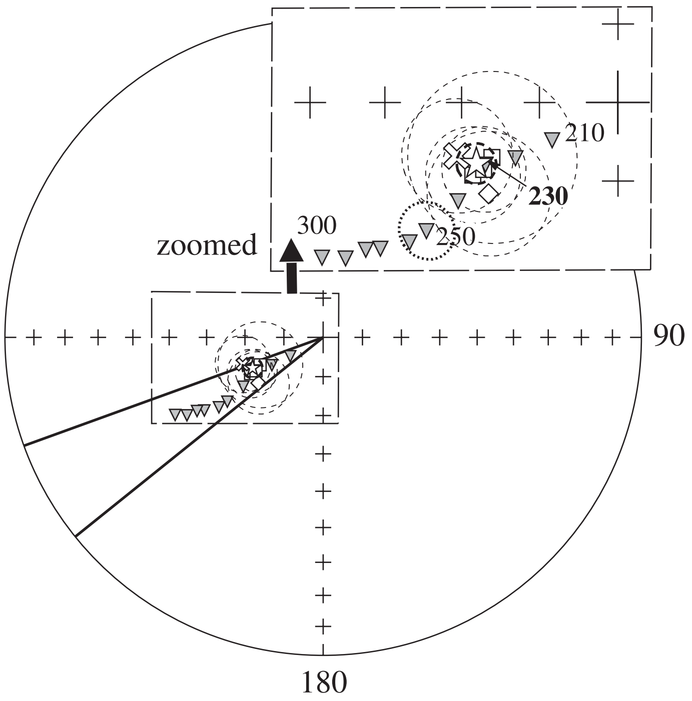

Figure 9. Stereonet of locality-mean overprint directions with confidence circles (thin lines): squares—locality-means in situ; oblique cross—the result for locality KN and DG (Kaynar-Dogolan) after 35% unfolding. Star—the overall mean direction with associated confidence circle (thick line). Diamond—recalculated (see text) mean direction with confidence circle (dashed-dotted line) from the ca. 248 Ma Semeitau igneous complex from north Kazakhstan (Lyons et al., 2002). Shaded triangles—reference directions recalculated from the apparent polar wander path (APWP) of Baltica with 10 m.y. increments (Torsvik et al., 2001). For clarity, the confidence circle is shown only for the 230 Ma direction. All data in (B) are upper hemisphere projections. Other notation as in Figure 4.

TABLE 2. SUMMARY OF OVERPRINT DIRECTIONS FROM NORTHEASTERN KAZAKHSTAN

		In situ					Tilt corrected			
Locality	N	A	D°	I°	k	α_{95}°	D°	I°	k	α_{95}°
KN and DG-A	(44/28)	35%	251.2	–68.2	16	7.2	220.3	–73.5	8	10.1
KU-comp. A	(18/12)	IS	243.5	–70.8	65	5.4	238.7	–45.3	20	9.9
GV	(6/6)	IS	243.4	–69.2	121	6.1	21.0	–62.4	25	13.7
SI	(18/5)	IS	246.4	–72.4	50	10.9	77.5	–56.6	<3	>60
Mean	[4/4]		246.2	–70.2	1304	2.5	249.5	–88.5	5	46.2

Note: A is coordinate system: 35% denotes the fact that component A at this locality is syn-tilting, estimated to have been acquired at 35% of the total tilting; IS denotes in situ data. Locality-mean overprint directions for Givetian (GV) and Lower Silurian (SI) rocks are from Levashova et al. (2003a). Mean is the overall mean overprint direction for KU, GV, and SI in situ, and KN and DG after 35% unfolding. N is the ratio of the number of (sites) [localities] studied and accepted. Other notation as in Table 1.

of the same field. Hence one explanation is to assume that secondary components may have been distorted by subsequent tilting; in our particular case, that would amount to a tilt of ~20° to the northeast. Such a tilt might be compatible with the observed fault network (Fig. 2); however, any supportive geological evidence of such tilting, which must have been uniform and yet affecting a rather large area, is absent.

A more likely solution is to assign somewhat younger ages to the remagnetization event. Latest Permian–Early Triassic magmatic rocks age are known in north Kazakhstan (Bekzhanov et al., 2000); one complex (Semeitau igneous suite), ~200 km to the north of our study area, has recently been dated as 248.2 ± 0.5 Ma by the ^{40}Ar/^{39}Ar method on sanidine (Lyons et al., 2002) and has given a paleopole that gives a direction (recalculated to our area; diamond in Fig. 9), which perfectly agrees with the overall mean of the secondary components. The Semeitau pole agrees well with a new mean pole on Siberian traps (Pavlov et al., 2007a). Arguing against this earliest Triassic age of the overprints, however, is that the reversal frequency close to the Permian-Triassic boundary was rather high (Opdyke and Channell, 1996), whereas normal polarity directions have not been observed in the Chingiz Range. We have difficulties imagining that the remagnetization event was of regional extent and yet very brief.

Thus it remains unclear whether overprint directions were of Kiaman age and distorted by younger deformation or whether they were acquired during a short remagnetization event near the Permian-Triassic boundary. Regardless, it is worth noting that all secondary directions from the Chingiz area concur both in declination and inclination with directions recalculated from the earliest Triassic apparent polar wander path (APWP) of Baltica (Torsvik et al., 2001), and thus, that they do not indicate any tilting, rotation, or relative displacements for such an age (Fig. 9).

Polarity Choice

The declinations from the rocks ranging in age from Late Cambrian to Middle Devonian from the Chingiz area are generally to the southeast or south, while the inclinations change from older and moderate up to younger, moderate down values (Table 1). In contrast, Permian directions are southwest and up (or rarely, northeast and downwards). We know that by Permian time, when Siberia, Tarim, Baltica, and the Kazakhstan areas were in the final stages of amalgamation, the study area must have been in the Northern Hemisphere, as uniformly agreed upon in the literature (e.g., Van der Voo, 1993; Didenko et al., 1994; Şengör and Natal'in, 1996; Smethurst et al., 1998a; Filippova et al., 2001; Stampfli and Borel, 2002; Kravchinsky et al., 2002a; Van der Voo et al., 2006; Cocks and Torsvik, 2007). Thus the NE-downward Permian directions represent normal polarity.

Carboniferous data from the Chingiz area are absent, but a dual-polarity result from Upper Carboniferous–Lower Permian rocks from the central arm of the Balkhash-Ili volcanic belt (Van der Voo et al., 2007) has an unambiguously normal polarity represented by NE and down directions. With respect to these late Paleozoic directions, and keeping the inclinations (and, hence, paleolatitudes) similar, the Early and Middle Devonian results display declinations that are clockwise rotated by more than 100° (Table 1). Devonian paleolatitudes were almost certainly in the Northern Hemisphere (see the above cited list of paleogeographic syntheses), implying that the Chingiz Range and vicinity suffered a large clockwise rotation in the interval between Middle Devonian and Early Permian time. The opposite polarity option would imply a highly unlikely motion through ca. 60° of latitude spanning the Southern and the Northern Hemisphere during the above time interval while all the surrounding tectonic elements stayed in the Northern Hemisphere.

Silurian declinations generally agree with the Devonian ones (Table 1), except for the locality SI result, which is likely to have been deflected by local rotation because of abundant strike-slip faults (Levashova et al., 2003a). It is logical to assume normal polarity for the southeasterly and upward early Paleozoic directions (Table 1) of Collins et al. (2003), which then imply Southern-Hemisphere positions and a crossing of the equator by the Chingiz area in Silurian times. The opposite option would require a reversal of the steady northward motion of the Chingiz area, as indicated by the Silurian to Permian data, in addition to another rotation of ~180° in the Middle to Late Ordovician. Note also that all major cratons like Siberia, Baltica, and Tarim were steadily moving northward in the Paleozoic, so that a Kazakhstan unit bucking this trend seems improbable. All in all, we conclude that the Chingiz area was moving northward through the Paleozoic from low southern to moderate northern latitudes.

Declinations and Rotations

The structural pattern of Kazakhstan is dominated by the strongly curved Devonian and late Paleozoic volcanic belts (Fig. 2), unconformably overlying older structures, which have been dismembered but still retain a suggestion of a horseshoe shape as well, e.g., for Ordovician subduction-related volcanics. Until the mid-Permian, the volcanics in the belts are of calc-alkaline affinity implying a continuous supra-subduction setting (Kurchavov, 1994; Tevelev, 2001). The horseshoe shape of the volcanic belts, marking the former subduction zone, has attracted attention of many geologists for a long time already. Some of them regarded the curvature of the volcanic belts as primary features (Zaytsev, 1984; Kurchavov, 2001), while others advocated oroclinal bending (Zonenshain et al., 1990; Şengör and Natal'in, 1996; Tevelev, 2001). The proponents of oroclinal bending are not so unanimous, however, insofar as the timing of the rotations is concerned.

After a first attempt to test the hypothesis of oroclinal bending by Grishin et al. (1997), concluding that about half of the strike contrast was due to vertical-axis rotations, Levashova et al. (2003a) compared Ordovician and Silurian data from the Chingiz Range (OE and SI, Table 1) with results from the North Tien Shan that revealed a Late Ordovician paleolatitude of ~8ºS (Bazhenov et al., 2003). They observed that the two arms of the giant horseshoe had declinations that differed from each other by ~180°, provided that both areas were located in low southerly paleolatitudes during the Ordovician.

With new paleomagnetic data from the southern limb of the late Paleozoic volcanic belt, Van der Voo et al. (2006) reanalyzed the problem and concluded that rotations were ubiquitous but that the pattern and sequence of events are complex. The two limbs underwent at least two episodes of vertical-axis rotational movements with respect to each other. Up to some 90° of rotation could be attributed to large-scale, east-west (present-day coordinates) sinistral wrenching in an intracontinental setting during the Permo-Triassic between Siberia and Baltica, as envisioned earlier by Natal'in and Şengör (2005). Noteworthy is that these rotations are widespread, but not uniform: some areas near strike-slip faults have rotated; other areas have not (Van der Voo et al., 2006). The remaining (and equally large) component of the observed declination deviations was left available for an interpretation in terms of pre-Permian oroclinal bending.

Most recently, Abrajevitch et al. (2007) combined Silurian and Devonian data from the volcanic belts, and first corrected for the post–Middle Permian rotations due to the just-described local small-scale block motions within the larger-scale sinistral wrench zone (Van der Voo et al., 2006). They could carry out such corrections, wherever (fortunately) Permian primary or overprint directions showed through their declination deviation what the magnitude of Late Permian–Early Triassic rotations had been. The mid-Paleozoic declinations, so corrected, now showed a remarkably consistent pattern, all generally pointing to the north in the southern arm (Fig. 10). Using the then-available Silurian and Devonian results from the Chingiz Range, Abrajevitch et al. (2007) could conclude that the strongly curved Devonian Volcanic Belt was originally a nearly rectilinear structure. Our current study puts the database from the northeastern arm on a much firmer footing and reconfirms the oroclinal rotations.

In the Chingiz area, there is no need for a correction for latest Paleozoic rotations, because the primary Permian and all Permo-Triassic remagnetization directions agree with each other and the reference paths of Baltica (Fig. 9). We can conclude that the primary Devonian and Silurian declinations reflect pre-Late Permian rotations only. As already noted, all these directions point to the southwest to (mostly) southeast (Fig. 10, Table 1), confirming the preliminary analysis of Abrajevitch et al. (2007) on oroclinal bending of the Devonian volcanic belt. The timing of this oroclinal bending remains constrained to the interval between Middle Devonian and Middle Permian in the absence of reliable Carboniferous paleomagnetic results from the northern and northeastern arms.

Paleolatitudes

In this section, we compare the paleolatitudes derived from the entire set of Paleozoic paleomagnetic data from the Chingiz with those of the major cratons around the Ural-Mongol mobile belt. Following paleomagnetic custom for such comparisons, we calculate reference paleolatitudes by extrapolation from an apparent polar wander path (APWP) for an optimal location in the area of interest; for this study we chose 48.5°N, 78.5°E within the Chingiz Range. Such a calculation is a prediction of the paleolatitude the Chingiz Range would have had, if it had stayed rigidly attached to the reference craton since the time of magnetization acquisition. Any deviation between prediction and an observed paleolatitude then becomes a measure of the relative displacements, in terms of latitudinal movements and relative rotations.

Only for Baltica does an adequately determined APWP exist for the entire interval of Early Ordovician through Late Permian. For Siberia, the data are unreliable for most of the middle and late Paleozoic (Cocks and Torsvik, 2007), with the exception of one good pole for ca. 360 Ma (Kravchinsky et al., 2002b), whereas the Tarim data set is simply too limited for construction of an APWP before Carboniferous times.

For Baltica, we can compute two versions (Fig. 11A), using the reference APWPs of Van der Voo (1993) and Smethurst et al. (1998b). The two plots concur reasonably well, despite

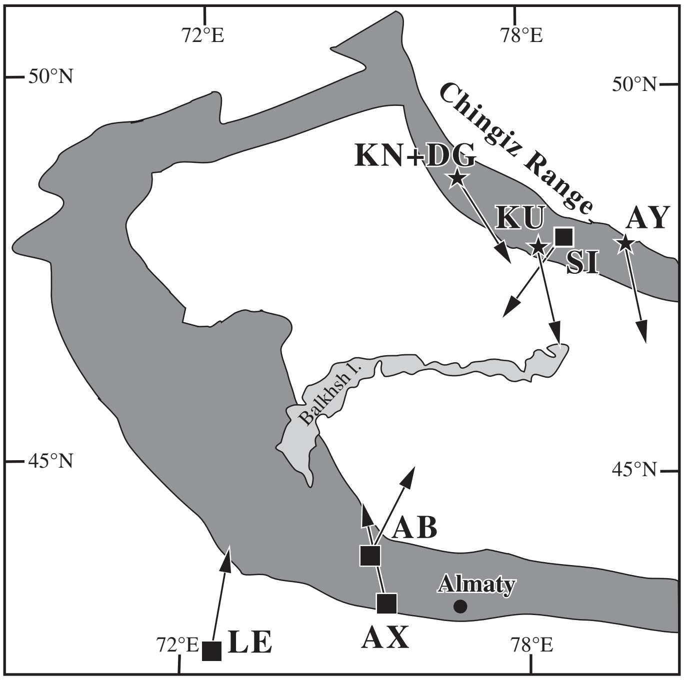

Figure 10. Schematic outline of the Devonian volcanic belt (gray; simplified from Fig. 2) with Silurian and Devonian paleomagnetic declinations (arrows). Only the results are shown that are based on full demagnetization and confirmed by positive field tests. Stars are the results from this study labeled as in the text. Published data (squares) are from: SI—Levashova et al. (2003a); AX—Alexyutin et al. (2005); AB—Abrajevitch et al. (2007); LE—Levashova et al. (2007). The last two results are corrected for Late Paleozoic rotations as described in Abrajevitch et al. (2007).

different selection criteria and smoothing approaches in constructing the APWP. To first approximation, the Chingiz observations show reasonable agreement with these plots for the Early Silurian–Late Permian interval. In contrast, the observed early Paleozoic paleolatitudes differ from the predicted ones, and show that there is much less poleward motion of Chingiz than what is extrapolated from Baltica for Cambrian and Ordovician time (Fig. 11A).

The reference APWP for Siberia became different after the ca. 360 Ma pole of Kravchinsky et al. (2002b) was published, as illustrated in Figure 11B. As our starting point, we used the APWP of Cocks and Torsvik (2007), who presented it in two options, CT-1 and CT-2, depending on whether the Early Permian pole of Pisarevsky et al. (2006) is included, or excluded, respectively (Fig. 11B). This result was presented as the first well-dated Early Permian pole for Siberia based on fully demagnetized data, but only five dikes could be studied, which is at the present time considered an inadequate quantity because it usually fails to average secular variation and other sources of noise. Our comparison of CT-1 predictions with primary Late Permian PA and PB poles shows (Fig. 11B) that the pole of Pisarevsky et al. (2006) would imply that Kazakhstan and Siberia had to converge by more than 3000 km in the Late Permian, which contradicts most available geological data. Due to these reasons, we have decided to prefer the comparison involving CT-2.

The post-Ordovician APWP of Cocks and Torsvik (2007) is based on very limited data, and the path strongly depends on the degree of smoothing by spline-fitting, which may introduce artificial maxima and minima during intervals with few or no data. To check on such problems we also use individual poles from Siberia instead of Cocks and Torsvik's APWP (Table 3; Fig. 11C). Because the data are abundant for the early Paleozoic, we included only results based on detailed demagnetization and principal component analysis.

Recently Shatsillo et al. (2007) published a paleomagnetic result from Early Silurian sedimentary rocks in Siberia. They isolated high-temperature, presumably primary components (#6, Table 3) as well as intermediate-temperature secondary components (#5, Table 3). The latter are inferred to be of Late Silurian–Early-Middle Devonian age. Their high-temperature Early Silurian pole is drastically different from a roughly coeval pole (#7, Table 3) of Torsvik et al. (1995). Because the latter result is based on only nine samples and coincides rather precisely with the remagnetization pole of Shatsillo et al. (2007), we have excluded #7 from Figure 11C.

A paleomagnetic pole of latest Silurian–earliest Devonian age was reported from the Tuva area to the south of the Siberian craton (see Fig. 1 for location) by Bachtadse et al. (2000). This area belongs to the mobile belt that borders the craton; geological data, however, indicate that the Tuva area docked to Siberia by Ordovician time (Mossakovsky et al., 1993; Dobretsov et al., 1995; Cocks and Torsvik, 2007). Of course, some rotations could occur and, moreover, Bachtadse et al. (2000) did document them. Our calculations show that the paleolatitude predicted for Chingiz from the Tuva result varied narrowly (±3º) unless the Tuva area underwent a later vertical-axis rotation >20º, which seems unlikely. Hence we used the Tuva result (#4) as a proxy for the cratonic pole and recalculated it to our study area. Additional confirmation of this comes from the fact that the Tuva pole of Bachtadse et al. (2000) and the overprint pole of Shatsillo et al. (2007) agree rather well, differing by ~7°.

With the comparison provided by the set of unit poles from Siberia (Fig. 11C), we find that the observed Cambrian, Ordovician, and Silurian paleolatitudes from Chingiz fall generally within its distribution, and the extrapolated Silurian–earliest Devonian paleolatitude from Tuva (#4) also agrees well with the average of our new KU and KN and DG results. Because the Silurian-Permian APWP for Siberia is still so sparsely populated, any comparison with Siberia's positions in this interval inevitably remains speculative. Nevertheless, the possibility is negligible that the data from Chingiz and Siberia show the good agreement of Figure 11C just by chance. This implies that these two units were moving for more than 100 m.y. in such a way that they retained a certain paleolatitudinal relationship that precludes large-scale separations (~>1500 km) unless followed quickly and dramatically by equally large reapproaches in what must be regarded as unlikely plate tectonic schemes for the 500–390 Ma interval. In other words, we cannot preclude, but find highly improbable, the notion that subsequent relative motions completely cancelled each other. To conclude this section, we favor the idea that Siberia and the Chingiz moved with a certain coherence after the Late Cambrian, similar to the conclusion we reached about the

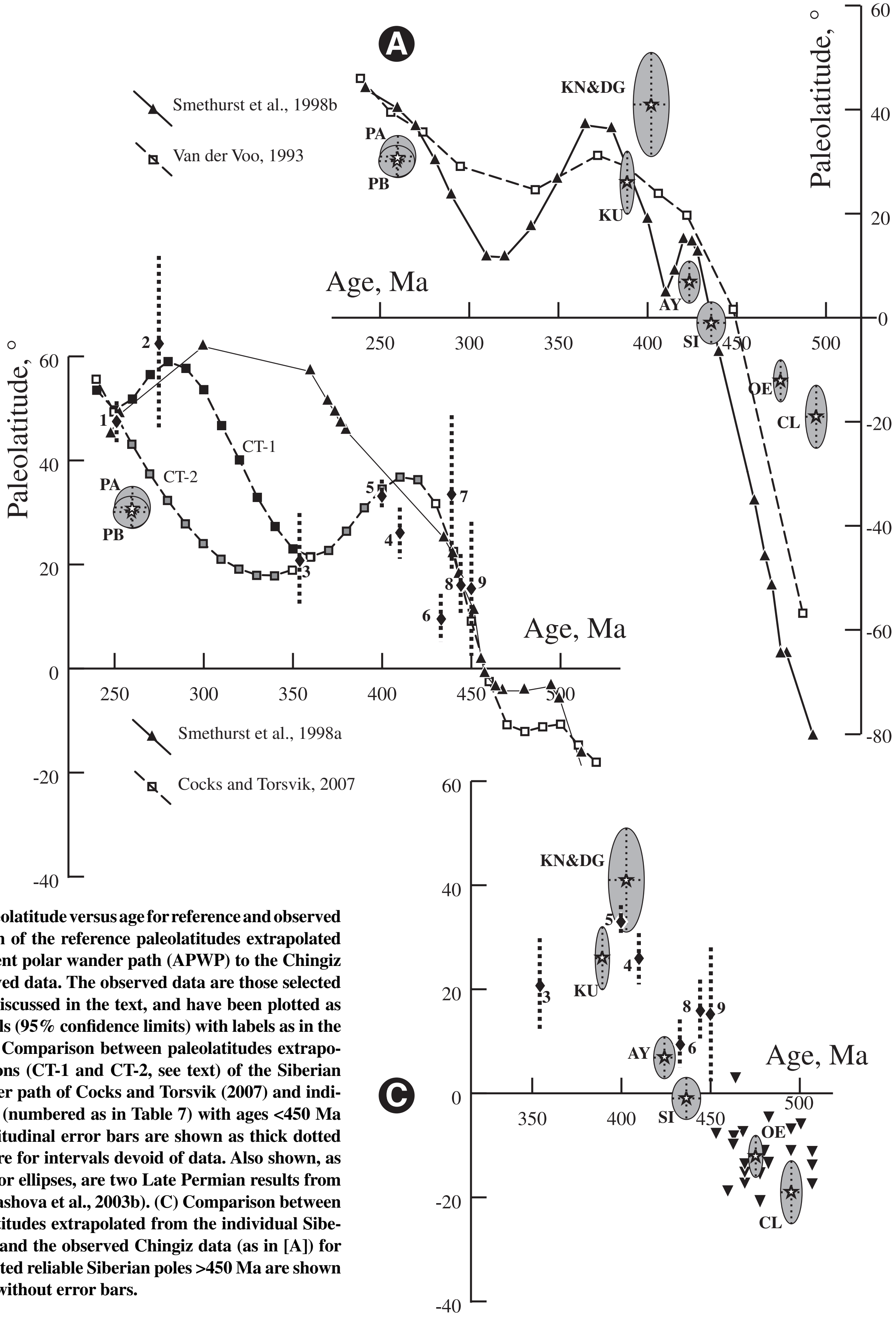

Figure 11. Plots of paleolatitude versus age for reference and observed data. (A) Comparison of the reference paleolatitudes extrapolated from Baltica's apparent polar wander path (APWP) to the Chingiz Range and the observed data. The observed data are those selected as more reliable, as discussed in the text, and have been plotted as stars with shaded ovals (95% confidence limits) with labels as in the text and Table 1. (B) Comparison between paleolatitudes extrapolated from two versions (CT-1 and CT-2, see text) of the Siberian apparent polar wander path of Cocks and Torsvik (2007) and individual Siberian poles (numbered as in Table 7) with ages <450 Ma (filled diamonds); latitudinal error bars are shown as thick dotted lines. Gray squares are for intervals devoid of data. Also shown, as stars with shaded error ellipses, are two Late Permian results from NE Kazakhstan (Levashova et al., 2003b). (C) Comparison between the reference paleolatitudes extrapolated from the individual Siberian poles (as in [B]) and the observed Chingiz data (as in [A]) for ca. 500–350 Ma. Selected reliable Siberian poles >450 Ma are shown as inverted triangles without error bars.

Baltica–North Tien Shan pair in an earlier report (Levashova et al., 2007).

Comparison with Published Paleogeographic Models

Not surprisingly, most of the thus far published paleogeographic models do not assume any kinematic affiliation between Siberia and Chingiz. According to several Russian authors (Mossakovsky et al., 1993; Didenko et al., 1994; Filippova et al., 2001; Kheraskova et al., 2003), the Ural-Mongol mobile belt was formed by the closure of the Paleoasian Ocean, in which an archipelago of scattered Precambrian microcontinents, oceanic basins, and island-arc segments existed in the Paleozoic. In their view, the most important role in the Ural-Mongol mobile belt amalgamation is played by diachronous opening and closing of the intervening oceans and, therefore, by similarly diachronous collisions of microcontinents and island arcs. The essential concepts of such models are similar, but they vary markedly in their details. For instance, Mossakovsky et al. (1993) and Didenko et al. (1994) assume that most microcontinents and island arcs docked to Siberia and formed a composite Kazakhstanian-Siberian continent in the Silurian, whereas Filippova et al. (2001) suggested that several of these units collided with each other first, thereby forming an independently moving mid-Paleozoic Kazakhstanian continent.

A different group of scenarios envisions the existence of a long and prominent volcanic arc system (Şengör and Natal'in, 1996; Yakubchuk et al., 2001, 2002; Stampfli and Borel, 2002). Şengör and Natal'in (1996), for instance, assumed that a continuous Kipchak Arc connected the Siberian and Baltica cratons in the early Paleozoic. In their views, arc motions are therefore linked to the kinematics of Siberia and Baltica, so that a certain coherence of the Siberian and Chingiz paleolatitudes, or those between Baltica and North Tien Shan, is to be expected. As is clear from our previous section, we see confirmation to some extent for these ideas in the paleomagnetic data (see also Levashova et al., 2007).

At the same time, much detail in the model of Şengör and Natal'in (1996) remains to be validated, as it assumes very specific kinematics of the major cratons. For example, from the Vendian until the end of the Devonian, Siberia would have to have been located ~2000 km to the north from Baltica (Fig. 12B). Such a configuration is necessary for the existence of a large ocean (called Khanty-Mansi) between Baltica and Siberia that is thought to have been bounded by the Kipchak Arc as a long-lived subduction feature. Further discussion

TABLE 3. PALEOZOIC PALEOMAGNETIC POLES OF SIBERIA

	Age		Poles				
N	ST	NU	ϕ°	Λ°	α_{95}°	Plat	Reference
1[#]	P_l-T_e	251	57.2	151.1	4.0	47.5	Pavlov et al., 2007a
2[##]	P_e	275	50.5	121.4	16.7	62.5	Pisarevsky et al., 2006
3	D_l-C_e	354	11.1	149.7	8.9	20.7	Kravchinsky et al., 2002b
4	S_l-D_e	410	–12	102	3	26	Bachtadse et al., 2000
5[§]	S_1-D_m	~400	–5.5	98.6	4.9	33.2	Shatsillo et al., 2007
6	S_e	433	–19.0	128.0	4.6	9.4	Shatsillo et al., 2007
7[##]	$O_l$as-S_e	439	3.1	118.1	14.8	33.4	Torsvik et al., 1995
8	$O_l$as-S_e	444	–13.9	124.1	5.9	15.7	Gallet and Pavlov, 1996
9	$O_l$as	450	–21	109	12.8	15.3	Torsvik et al., 1995
10	O_l	453	–31.6	140.5	6.9	–7.3	Pavlov et al., 2003
11	$O_m$ld	463	–24.1	152.4	3.3	–7.9	Pavlov et al., 2007b
12	$O_m$ld	463	–22.7	157.6	2.8	–10.0	Gallet and Pavlov, 1996
13[§§]	O_m	464	–27.6	124.8	4.0	3.4	Iosifidi et al., 1999
14	O_m	468	–32	139	2.2	–6.9	Torsvik et al., 1995
15	$O_m$lv	469	–35.2	153.2	3.6	–16.8	Pavlov et al., 2003
16	$O_m$lv	469	–30.9	152.7	2.8	–13.3	Pavlov and Gallet, 1998
17	$O_m$lv	469	–29.8	156.6	3.1	–14.7	Gallet and Pavlov, 1996
18	$O_e$ar	478	–36.4	158.2	6.5	–20.4	Pavlov et al., 2003
19	$O_e$ar	478	–33.9	151.7	1.9	–15.0	Gallet and Pavlov, 1996
20	O_e	480	–42.2	128.1	5.8	–10.7	Surkis et al., 1999
21	$O_e$tr	483	–35.2	127.2	4.1	–4.3	Pavlov and Gallet, 1998
22	$O_e$tr	483	–40.3	137.5	6.9	–13.0	Gallet et Pavlov, 1996
23	Cm_l	495	–36.1	130.7	2.6	–6.5	Rodionov et al., 2003
24	Cm_l	495	–37.0	138.4	4.8	–10.7	Gallet et Pavlov, 1996
25	Cm_m	501	–37.7	124.0	4.5	–5.2	Rodionov et al., 1998
26	Cm_m	507	–41.9	135.8	2.3	–13.5	Pavlov and Gallet, 2001
27	Cm_m	507	–43.7	140.5	2.6	–17	Gallet et al., 2003
28	Cm_m	507	–36.4	139.6	4.0	–10.8	Pisarevsky et al., 1997

Note: Ages of the rocks (components) are as inferred by the authors of the data: ST—stratigraphic age (as—Ashgillian; ld—Llandeilian; lv—Llanvirnian; ar—Arenigian; tr—Tremadocian); NU—numerical age interpolated from Geologic Time Scale (Gradstein et al., 2004). Poles are given as latitude (ϕ) and longitude (Λ) of the north poles together with corresponding radii of the 95% confidence circle (α_{95}). Plat—paleoaltitude of the reference point at 48.5°N, 78.5°E, calculated by extrapolation from the entry's paleopole.

[#] The overall mean pole for the Siberian traps (NSP4 pole from Pavlov et al., 2007).

[##] Discarded from our analysis (see text).

[§] Overprint combined mean pole from Shatsillo et al. (2007) of presumably Late Silurian–Middle Devonian age.

[§§] We used one pole for combined normal and reversed data from the Middle Ordovician rocks (Iosifidi et al., 1999) in contrast to Cocks and Torsvik (2007), who used two poles (for normal and reverse polarity separately) in their compilation.

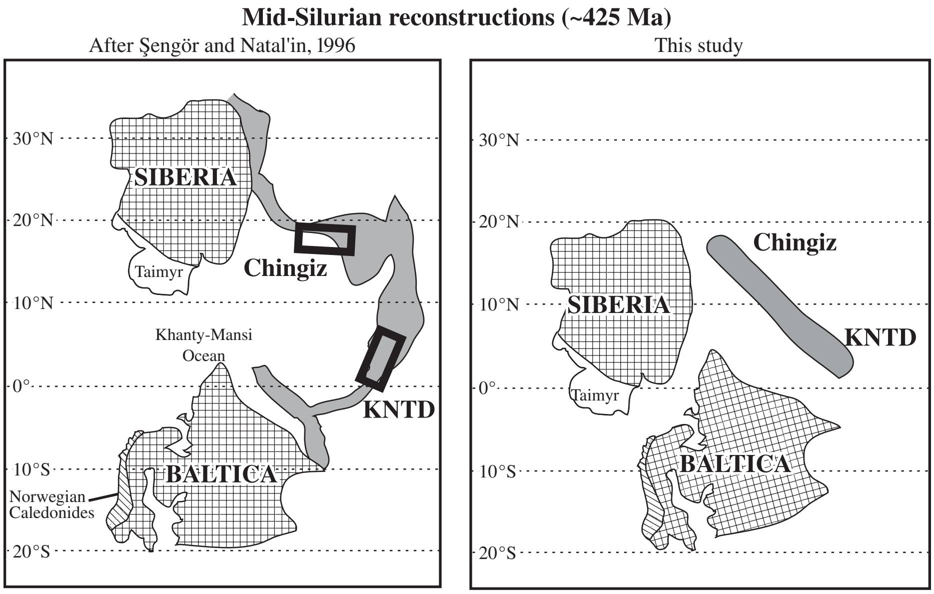

Figure 12. Reconstruction of the Ural-Mongol belt and the major cratons of Baltica and Siberia (cross-hatched) for mid-Silurian time. (A) Reconstruction after Şengör and Natal'in (1996). Note ~2000 km latitudinal separation of Baltica and Siberia and complicated form of external active margin of the Ural-Mongol belt (gray). (B) The position of Siberia is in accord with the new paleopole of Shatsillo et al. (2007); the Devonian volcanic belt and adjacent parts of Kazakhstan are shown as a rectilinear ribbon continent (shaded). See text for more detail. KNTD—Kokchetav–North Tien Shan.

of this topic is outside the scope of this paper, not because it is irrelevant, but because with the paleomagnetic contributions of our studies we cannot make inroads toward resolution or rejection of several such aspects.

The Early Silurian pole of Shatsillo et al. (2007) places Siberia closer to Baltica than most other paleogeographic portrayals for Silurian time, and also closer than is typically shown for Ordovician or Devonian times. Thus, it appears that the relative positions of Baltica and Siberia in the middle Paleozoic may have varied to some extent. We make an attempt to show schematically the paleogeography of Baltica, Kazakhstan, and Siberia, while satisfying the following constraints: (1) the Chingiz is moving in accord with, and remains close to, Siberia (this study); (2) the Kokchetav–North Tien Shan domain is moving approximately in accord with Baltica (Levashova et al., 2007); (3) the original Devonian volcanic belt is rectilinear and trends ~135° (Abrajevitch et al., 2007); and (4) Baltica and Siberia are in the latitudinal positions mandated by their paleomagnetic data.

Note in particular that (1) and (2) do not imply an absolutely rigid connection between the cratons and Ural-Mongol mobile belt units, but suggest rather that a limit should be placed on the possible relative motions between them to a value of 1000 km or less.

With this information and limits in mind, we propose a schematic reconstruction of Baltica, Kazakhstan, and Siberia for mid-Silurian time (Fig. 12B). The reconstruction differs from previous paleogeographic configurations in a more westerly position of Siberia with respect to Baltica as well as a nearly rectilinear "ribbon" Kazakhstan continent, which is in sharp contrast to much more complicated predictions of other authors.

CONCLUSIONS

Our paleomagnetic study of mid-Silurian to Middle Devonian volcanics from three localities in the Chingiz Range of NE Kazakhstan yields characteristic and likely primary magnetizations as well as overprint directions. The agreement of the latter data with extrapolated earliest Triassic predictions from Baltica or Siberia implies that strike-slip fault-related rotations are not present in the Chingiz Range, unlike the abundance of such rotations in the North Tien Shan branch of the Balkhash-Ili volcanic belt (Van der Voo et al., 2006). In contrast, presumed primary declinations indicate a very large rotation of the Chingiz area after the Middle Devonian, with respect to Baltica as well as the North Tien Shan. This rotation fits into a model that advocates oroclinal bending of up to 180º within the strongly curved Devonian volcanic belt of Kazakhstan (Abrajevitch et al., 2007).

We find, in contrast with most previous paleogeographic models, that the Chingiz block has not been far away from the Siberian craton during much of the Paleozoic. In turn, this requires a considerable revision of existing and rather disparate paleogeographic models for Central Asia. We do present a possible paleogeography of Baltica, Siberia, and Kazakhstan for mid-Silurian time at ca. 425 Ma (Fig. 12B) but would like to stress that this very schematic reconstruction is just a passing stage on the road to improved understanding of the process of Eurasia amalgamation.

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Table 1. Site-mean paleomagnetic directions for the Silurian rocks from locality AY

			In Situ		Tilt corrected			
Site	N	A	D°	I°	D°	I°	k	α_{95}°
M9066	7/7	124/20	153.4	29.3	149.9	11.5	18	14.9
N3801	7/7	124/20	168.6	35.2	161.7	20.0	50	8.6
M9073	6/5	135/45	198.2	61.8	163.6	28.2	25	16.1
M9079	12/7	135/45	206.9	49.9	176.9	23.6	41	9.6
M9111	6/6	135/45	192.8	21.1	187.5	-5.6	40	10.8
M9117	7/7	135/45	182.1	31.8	173.6	-2.1	285	3.6
N3808	6/6	134/39	184.0	60.8	158.6	23.0	75	7.8
N3814	6/6	134/39	184.5	55.2	162.2	18.6	151	5.5
N3820	6/6	135/45	186.5	55.5	163.1	19.4	38	11.0
N3826	7/7	135/45	179.8	35.9	169.8	0.5	194	4.3
N3833	6/6	135/45	204.2	38.4	184.0	14.0	123	6.1
N3839	7/7	135/45	175.7	42.3	163.9	4.6	139	5.1
MEAN	(12/12)		183.7	44.1			22	9.5
					168.0	13.2	28	8.4

Comments: N is the ratio of the number of samples (sites) studied/accepted; A is the site's azimuth of dip/dip angle; D, declination; I, inclination; k, concentration parameter; α_{95}, radius of 95% confidence circle (Fisher, 1953). The results are presented in stratigraphic order from top to bottom.

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Table 2. Component A data from Lower-Middle Devonian rocks from localities KN and DG

			In Situ				Tilt corrected			
Site	N	A	D°	I°	k	α_{95}°	D°	I°	k	α_{95}°
A44	5/4	8/50	328.9	-63.6	52	12.9	218.6	-57.3	52	12.9
A61	7/0	328/25	No stable remanence above 250°							
A68	6/3	330/24	272.3	-45.2	55	16.7	245.3	-53.4	55	16.7
A75	6/0	fold	scattered							
A81	6/5	297/24	223.7	-37.8	63	10.0	203.8	-40.9	63	10.0
A87	4/0	313/21	No stable remanence above 250°							
A93[#]	6/3	216/26	224.3	-2.2	62	15.7	225.4	-27.8	62	15.7
M8019	7/4	350/28	326.3	-59.0	86	9.9	263.7	-78.2	86	9.9
M8026	9/6	350/28	305.8	-49.7	19	15.6	266.5	-63.2	19	15.6
M8044	6/4	143/15	188.2	-71.6	79	11.0	240.7	-76.9	79	11.0
M8050	5/3	168/20	231.4	-59.3	50	17.6	267.8	-62.3	50	17.6
M8056	5/2	168/20	249.2	-66.1	-	-	290.3	-61.5	-	-
M8062	5/3	168/20	270.2	-60.4	13	35.4	297.2	-51.2	13	35.4
P200	5/5	358/55	335.7	-67.5	185	5.6	192.1	-55.2	185	5.6
P218	6/4	260/14	223.2	-81.2	19	21.8	119.3	-81.8	19	21.5
P248	6/0	8/37	scattered							
P254	6/0	348/34	Main component is close to the present-day field							
P260	6/4	331/36	284.2	-56.3	74	10.8	216.5	-63.9	74	10.8
P266	6/6	294/29	278.0	-62.5	358	3.5	185.4	-82.5	358	3.5
A99	4/4	246/44	258.1	-27.1	22	23.5	277.7	-69.0	43	16.4
A112	4/0	263/44	scattered							
A190	7/4	12/34	155.2	-81.6	25	20.0	184.6	-49.4	25	20.0
A300	5/5	12/32	280.9	-56.4	11	24.3	242.6	-44.6	11	24.3
M8161	3/0	356/46	scattered							
M8167	3/0	356/46	scattered							
M8174	3/3	1/35	312.7	-53.6	37	24.1	253.5	-62.6	37	24.1
M8180	6/6	358/38	252.9	-63.0	36	11.3	212.1	-39.1	36	11.3
M8187	5/3	1/41	217.1	-51.8	51	17.4	203.0	-15.5	51	17.4
P306	6/5	252/43	248.2	-24.1	132	6.7	243.7	-66.9	132	6.7
P312	6/6	245/60	252.6	-43.3	116	6.3	41.1	-75.2	116	6.3
P317	6/6	245/60	217.5	-46.4	403	3.3	109.2	-63.4	403	3.3
P357	5/5	263/47	199.3	-70.6	30	14.2	109.4	-48.8	30	14.2
P362	9/5	263/47	226.6	-74.9	47	11.3	97.9	-54.4	47	11.3
P371	6/6	248/40	259.6	-60.2	158	5.4	38.6	-77.7	158	5.4
P377	5/5	248/40	274.4	-59.8	100	7.7	20.6	-71.9	100	7.7
P383	6/5	348/40	308.8	-74.8	38	12.7	187.1	-60.5	38	12.7
P389	6/6	348/40	305.6	-58.5	90	7.2	222.0	-64.5	90	7.2
T50	5/0	17/32	scattered							
Mean1	(44/27)		261.4	-63.2	12	8.3	220.3	-73.5	8	10.1
Mean2	(44/22)		261.4	-61.6	11	9.7	209.1	-73.4	8	11.6
35% unfold	(44/27)		251.2	-68.2	16	7.2				

[#] – this anomalous site is excluded from computation of the overall mean.

Mean1 (Mean2) is the overall mean direction of all sites (sites with more than two samples and $\alpha_{95} < 20°$). 35% unfold is the mean direction at 35% incremental unfolding. Other notation is as in Table 1.

Table 3. Component B data from Lower-Middle Devonian rocks from localities KN and DG

		In Situ					Tilt corrected			
Site	N	A	D°	I°	k	α_{95}°	D°	I°	k	α_{95}°
A44	5/3	8/50	163.2	30.3	162	9.7	116.2	67.9	162	9.7
A81	6/4	297/24	157.4	47.6	55	17.0	186.0	61.9	55	17.0
M8019$^{\#}$	7/4	350/28	348.9	22.9	226	6.5	348.9	-5.1	226	6.5
M8037	6/4	338/40	349.0	-35.1	100	9.2	11.0	-73.0	100	9.2
M8044	6/6	143/15	102.0	63.5	125	6.1	115.2	50.9	125	6.1
M8050	5/2	168/20	303.3	-60.4	-	-	318.9	-44.1	-	-
M8056	5/3	168/20	309.8	-69.6	66	15.3	327.3	-51.9	66	15.3
M8062	5/4	168/20	297.9	-53.6	36	15.5	312.2	-38.7	36	15.5
P200	5/5	358/55	176.2	32.3	136	7.1	153.7	87.0	136	7.1
P206	5/5	348/50	158.0	15.5	237	5.0	146.1	64.1	237	5.0
P211	7/6	348/50	157.4	23.2	220	4.5	137.4	71.1	220	4.5
P218$^{\#}$	6/4	259/14	264.4	74.1	126	11.0	262.1	60.5	106	12.0
P266	6/2	294/29	318.8	-30.6	-	-	333.7	-55.4	-	-
A166	5/5	16/31	171.2	22.2	87	8.8	159.6	49.0	97	8.4
A172	6/6	16/23	163.9	16.3	118	6.3	157.1	35.4	118	6.3
A180	2/2	13/26	165.1	23.9	-	-	155.7	46.6	-	-
A190$^{\#}$	7/6	12/33	92.4	-41.8	159	5.4	121.7	-38.7	159	5.4
M8167	3/3	356/46	337.5	-40.4	50	20.6	274.2	-76.1	50	20.6
M8187	5/5	1/41	158.9	0.9	24	17.0	152.4	38.4	24	17.0
P362	9/5	263/47	107.3	38.2	35	14.1	166.7	70.7	35	14.1
P371	6/4	248/40	90.8	46.7	48	15.6	154.6	74.3	48	15.6
Reverse	(6)		322.8	-49.8	16	17.2	322.8	-58.2	18	16.4
Normal	(12)		152.6	32.5	9	15.7	150.4	61.1	20	10.0
Mean1	(44/18)		149.8	38.6	10	11.9	147.7	60.2	20	8.0
Mean2	(44/14)		150.0	38.2	8	14.8	149.1	61.2	19	9.4

$^{\#}$ – this anomalous site is excluded from computation of the overall mean.

Mean1(Mean2) is the overall mean direction of all sites (sites with more than two samples and $\alpha_{95} < 20°$). Other notation is as in Table 1.

Table 4. Paleomagnetic data from Givetian (Middle Devonian) volcanics (locality KU)

		In Situ					Tilt corrected			
Site	N	A	D°	I°	k	α_{95}°	D°	I°	k	α_{95}°
Intermediate-temperature A component										
M9198	7/4	63/48	261.2	-72.5	183	6.8	249.0	-25.2	183	6.8
M9205	6/5	62/41	269.7	-72.2	29	15.6	251.7	-32.8	29	15.6
M9211	6/6	62/41	294.6	-78.1	135	6.0	254.6	-41.0	135	6.0
M9217[#]	6/6	269/16	276.5	-25.7	11	21.2	278.1	-41.5	11	21.2
M9223	6/4	54/38	219.1	-59.7	19	21.8	226.0	-22.4	19	21.8
N3858	7/7	9/22	246.3	-70.7	102	6.0	217.2	-53.9	102	6.0
N3865	6/6	9/22	238.0	-55.3	84	7.7	224.3	-38.5	84	7.7
N3871	6/6	9/22	234.6	-67.2	24	13.9	213.9	-48.9	24	13.9
N3883[#]	6/6	269/16	143.9	-47.1	32	11.9	132.9	-36.6	32	11.9
D7	7/6	85/20	278.0	-79.9	44	10.2	269.5	-60.1	44	10.2
D8	7/3	85/20	269.6	-67.6	47	18.1	267.6	-47.6	47	18.1
D9	7/6	85/20	235.6	-66.2	22	14.8	247.9	-47.7	22	14.8
D10	6/6	85/20	232.2	-73.8	15	17.8	249.6	-55.3	15	17.8
D11	7/6	85/20	262.7	-72.4	16	17.2	263.9	-52.4	16	17.2
Mean	(18/12)		248.5	-70.8	65	5.4	243.9	-45.3	20	9.9
High-temperature B component										
m9198	7/7	63/48	187.3	33.5	37	11.5	145.0	46.0	37	11.5
M9205-GC	*6/4*	*62/41*	*107.8*	*-20.5*	-	*7.1*	*130.5*	*-43.8*	-	*7.1*
M9211-GC	*6/4*	*62/41*	*99.2-*	*14.5*	-	*29.2*	*116.5*	*-44.1*	-	*29.2*
N3865-GC	*6/4*	*9/22*	*230.9*	*-49.3*	-	*8.7*	*219.7*	*-31.4*	-	*8.7*
N3871-GC	*6/3*	*9/22*	*96.5*	*-17.8*	-	*25.9*	*103.5*	*-17.5*	-	*25.9*
N3877	6/6	9/22	163.6	25.3	33	12.7	171.6	28.5	33	12.7
D7	7/4	85/20	0.7	-43.8	12	27.1	341.0	-44.4	12	27.1
D8	7/6	85/20	6.0	-53.1	53	9.9	338.3	-54.3	53	9.9
D9	7/7	85/20	18.1	-40.5	63	7.9	359.7	-47.4	63	7.9
D11	7/5	85/20	26.2	-38.3	217	5.4	9.5	-48.1	217	5.4
North	(4)		13.4-	44.4	58	12.1	352.4	-49.3	58	12.1
South	(6)		178.2	30.7	64	9.4	162.3	40.0	38	12.3
Mean	(18/10)		183.9	38.4	34	8.5	167.0	44.3	41	7.8

[#] - two anomalous sites were excluded from the computation of mean A-component directions; entries in italics represent great-circle poles rather than declinations and inclinations. North (South) are polarity-means for northward (southward) pointing directions, Other notations as in Tables 1 and 3.