Paleozoic Geography and Paleomagnetism of Kazakhstan

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Contents

Preamble

Parts of this thesis are based on (or directly taken from) papers or abstracts published or to be published in international scientific journals. These are listed below.

Alexyutin, M. V., Bachtadse V., Alexeiev, D.V., Nikitina, O.I., "Paleomagnetism of the Ordovician and Silurian rocks from the Chu-Yili and Kendyktas mountains, South Kazakhstan." Geophysical Journal International, 162 (2), 321-331, 2005.

Alexyutin, M.V., Alexeiev D.V., Nikitina O. I., Bachtadse V., Middle and Late Paleozoic Paleomagnetism of Southern Kazakhstan, Geophys. J. Int. (submitted)

Alexyutin, M.V., Bachtadse V., Alexeiev, D.V., Nikitina, O.I., Paleomagnetism of Palaeozoic rocks from South Kazakhstan: Preliminary results and interpretation, in *EGS-AGU-EUG Joint Assembly*, Nice, 2003.

Alexyutin, M.V., Bachtadse V., Alexeiev, D.V., Paleomagnetism of the Devonian and Carboniferous rocks from Chu-Yili mountains, Southern Kazakhstan, in *EUG Meeting*, Nice, 2004.

Alexyutin, M.V., Bachtadse V., Alexeiev, D.V., Paleomagnetism of Silurian and Devonian rocks from Central and Northern Kazakhstan - comparison with South Kazakhstan directions, in *AUG Meeting*, *San Francisco*, 2004.

Zusammenfassung

Der Norden Eurasiens besteht aus einer Vielzahl kontinentaler Blöcke (Baltika, Europa, Sibirien, Kasachstan, Turan und Tarim), die während des Karbons und Perms kollidierten. Der paläozoische Kontinent Kasachstan befindet sich im Zentrum dieses Agglomerats. Erkenntnisse zur tektonischen Entwicklung dieses Gebiets sind von großer Bedeutung für die Interpretation der geologischen Geschichte Eurasiens.

Bei der Interpretation der paläozoischen Geschichte Kasachstans treten jedoch Komplikationen auf und regionale geodynamische Modelle stehen oft schon bei grundlegenden Annahmen im Widerspruch zueinander [Zaitsev, 1984; Zonenshain, et al., 1990; Mossakovskiy et al. 1993; Sengör et al. 1993]. Prinzipielle Streitpunkte treten vor allem bei folgenden Punkten auf:

(a) Der Eingrenzung und Identifikation eigenständiger Terranes, die heute in Kasachstan integriert sind; (b) Der Rekonstruktion von Driftbewegungen der einzelnen Terranes, bzw. des gesamten kasachischen Kontinents; (c) der nach der primären Geometrie des paläozoischen gefalteten Gürtels, der heute als riesige gebogene Struktur (Orokline) die Tektonik Kasachstans dominiert.

Eine Klärung existierender Ungereimtheiten ist hauptsächlich durch die geringe Anzahl qualitativ hochwertiger paläomagnetischer Daten aus Kasachstan erschwert.

Entsprechend wurden paläomagnetische Untersuchungen, basierend auf oben genannten offenen Fragen, in Südkasachstan durchgeführt. Gesteine des Unteren Ordoviziums bis Karbons mit ausgezeichneten Faltenstrukturen und guter biostratigraphischer Alterskontrolle wurden beprobt. Insgesamt 16 Lokalitäten (187 Aufschlüsse. 1100 Proben) unterschiedlichen Alters und Lithologie wurden untersucht. Magnetische Komponenten, die vor der Faltung erworben wurden, wurden im unteren Ordovizium (unteres Arenigian), Silur, unteren bis mittleren Devon und im unteren Karbon nachgewiesen.

Die paläomagnetische Daten für Redbeds des unteren Arenigian (D= 9.2°, I=-16.9°, k=26.9, α_{95}=15.0°) sind erste und bisher einzige Richtungen, die überhaupt für die Zeit, als die allochthonen Terranes noch getrennt voneinander existierten, ermittelt wurden.

Richtungen des „South-Chu-Yili“ Gebirges (Silur bis unteres Devon, D = 346.9°, I=23.8°) zeigen nördliche Deklinationen und positive Inklinationen. Daraus resultiert bei angenommener normaler Polarität eine nördliche Paläobreite von etwa 12.4° ± 7.7°.

Das erstaunlichste Ergebnis dieser Studie liefert die Koktas Formation (unteres Devon, D= 357.3°, I=+75.8°), bei welcher die paläomagnetischen Richtungen signifikant von den

Referenzrichtungen für Baltika und Sibirien abweichen. Die ermittelte nördliche Paläobreite von 64° übersteigt alle für das Paläozoikum erwarteten Werte.

Die Remanenzkomponente aus Redbeds des Kendyktas Rückens (oberes Devon – unteres Karbon, D=069.5°, I=+43.7°, k=26.7, $\alpha95$=9.5°) resultiert in einer Paläobreite von etwa 21.8° ± 5.9° N.

Die Daten dieser Studie sowie Veröffentlichungen vergangener Jahre lassen keine Rückschlüsse auf bedeutende Unterschiede bei den Paläobreiten Nord- und Südkasachstans seit dem mittleren Ordovizium zu. Allerdings weisen die Mehrzahl der paläomagnetischen Daten darauf hin, dass sowohl Süd- als auch Nordkasachstan während des Paläozoikums wahrscheinlich etwas weiter im Norden, bzw. etwas weiter im Süden positioniert waren als erwartungsgemäß als Teil Baltikas, bzw. Sibiriens. Während des Ordoviziums bis Perms driftete Kasachstan mit einer zur Bewegung Baltikas und Sibiriens vergleichbaren Geschwindigkeit Richtung Norden.

Die Verteilung kasachischer Richtungen deutet mehrere Phasen magnetischer Überprägung mit signifikanter regionaler Ausbreitung an. Eine in Baltika sehr verbreitet auftretende permische Überprägung spielt dabei nur eine untergeordnete Rolle.

Die in Südkasachstan nachgewiesenen Rotationen können nicht mit dem tektonischen Modell zur Entwicklung des Kipchak Bogens von Sengör et al. [1993] und Sengör and Natal'in [1996] in Übereinstimmung gebracht werden, nach dem Rotationen von rund 90° im Uhrzeigersinn relativ zu Baltika, bzw. rund 30° relativ zu Sibirien seit dem unteren Devon zu erwarten wären. Die paläomagnetischen Ergebnisse [diese Studie, Bazhenov, et al, 2003] zeigen im Gegensatz Rotationen gegen den Uhrzeigersinn.

Es wird eine modifizierte Polwanderkurve für Kasachstan vorgestellt, die auf jüngeren, qualitativ hochwertigeren paläomagnetischen Daten basiert.

Die Hypothese von Sengör and Natal'in [1996] (oroclinal bending) wird abgelehnt, stattdessen wird ein Modell entwickelt, mit dem die gekrümmten Strukturen Kasachstans mit Plattentektonik im klassischen Sinne erklärt werden können.

Summary

The northern part of Eurasia consists of several continental blocks (Baltica, Siberia, Kazakhstan, Turan and Tarim), which were welded together during Carboniferous and Permian times. Within this agglomerate, the Paleozoic continent of Kazakhstan occupies a central position, and recognizing the tectonic evolution of this area is of great importance for understanding the geological history of entire Eurasia.

The interpretation of the Paleozoic history of Kazakhstan meets certain difficulties and regional geodynamic models are contradicting even on basic assumptions and interpretations [Zaytsev, 1984; Zonenshain, et al., 1990a; Sengör et al. 1993]. Principal questions are related to (a) the identification of individual terranes, now integrated into Kazakhstan, (b) the reconstruction of the drift histories of these terranes prior to amalgamation an the drift history of the Kazakhstan continent after amalgamation, (c) the definition of the origin of the curvature of the Paleozoic folded belts, which form a giant tight loop. Resolving existing uncertainties is hampered mostly by the scarcity of reliable paleomagnetic data for the Paleozoic of Kazakhstan.

Addressing the unsolved problems of Paleozoic geodynamics of Kazakhstan, a paleomagnetic study has been conducted in South Kazakhstan. The rocks exposed here range in age from the Lower Ordovician to the Carboniferous, with well expressed fold structures and biostratigraphic control. In total 16 localities (187 sites, 1100 samples) with different ages and lithologies were investigated. Prefolding components of magnetization have been isolated in Lower Ordovician (the Lower Arenigian), Silurian, Lower to Middle Devonian, and Lower Carboniferous formations.

The pre-folding component of magnetization from the Lower Arenigian red-beds (D= 9.2°, I=-16.9°, k=26.9, α_{95}=15.0°), defines the location of one of the major Lower Paleozoic microcontinents of Kazakhstan during a period of time, when all Kazakh terranes were still separated from each other. This is the first and only case in Kazakhstan where paleomagnetic data were obtained for one of the original terranes before amalgamation.

The pre-folding components of magnetization isolated in the Silurian and Lower Devonian rocks in the South Chu-Yili mountains show a northerly declination and positive inclination (D = 346.9°, I =23.8°) and indicate a northerly paleolatitude of the area of 12.4° ± 7.7° if a normal polarity is assumed.

The most striking result obtained in this study is probably the direction of the pre-folding component of magnetization identified in rocks of early Devonian age from the Koktas formation (D= 357.3°, I=+75.8°, k=16.5, α95=14.1°), which is significantly different from both

the reference directions for Baltica and Siberia. The resulting paleolatitude of 64° exceeds any expected value for the Paleozoic.

In the Kendyktas ridge, a pre-folding component of magnetization (D=069.5°, I=+43.7°, k=26.7, α95=9.5°) was isolated in the Upper Devonian – and Lower Carboniferous red beds implies a paleolatitude of 21.8° ± 5.9° N.

Based on the data from this study and the data published during the last decade it becomes obvious that since the Middle Ordovician, North and South Kazakhstan show no significant difference in latitudinal positions. The majority of the paleomagnetic data indicate that in the Palaeozoic, both South and North Kazakhstan were situated slightly further to the North than it would be expected if Kazakhstan was a part of Baltica, or slightly further to the South than it would be expected if Kazakhstan was a part of Siberia. Since the Ordovician up to the Permian, Kazakhstan moved from southern latitudes into northern latitudes with drift rates close to those of Baltica and Siberia.

The distribution of postfolding components from South Kazakhstan indicates that Kazahkstan was affected by several remagnetization events of significant regional extent. Surprisingly, however, Permian remagnetizations, widespread in Baltica, only play a minor role.

The paleomagnetic rotations observed for South Kazakhstan cannot be reconciled with tectonic models such as the one for the evolution of the Kipchak arc [Sengör et al., 1993; Sengör and Natal'in, 1996]. This model assumes, that since the Early Devonian southern Kazakhstan had experienced clockwise rotation of about 90° relative to Baltica and about 30° clockwise rotation with respect to Siberia. This is in contrast to paleomagnetic results [this study, Bazhenov, et al, 2003] indicating counterclockwise rotation.

As a result of this study the APWP of Kazakhstan has been reviewed using modern paleomagnetic results.

The tectonic model suggested in this study is able to explain the bent structures of Kazakhstan within the classic conception of plate tectonic, contradicting the hypothesis of orocline bending proposed by Sengör and Natal'in (1996).

Introduction

Within the framework of geosciences paleomagnetism is positioned at the junction of geology and geophysics. More than 150 years ago, the natural phenomenon of remanent magnetization in lavas has been recognized. Since that time, it has become evident that most rocks possess a natural remanent magnetization, and that this magnetization represents a record of the ancient magnetic field. As soon as it was possible to read and understand this information, geologists have received a very powerful tool to solve problems concerning various aspects of the past of the Earth.

Today, several main branches of this science – rock magnetism, magnetostratigraphy and magnetotectonics, positioned at the junction of paleomagnetism with lithology, stratigraphy and tectonics – are firmly established.

Among the various methods, used for paleotectonic reconstructions, only paleomagnetism provides us with qualitative and quantitative information on the paleoposition of tectonostratigraphic units of various sizes in the past. The fundamental basis for paleomagnetism is the observation that the magnetic field can be described as a geocentric axial dipole (GAD), where the inclination of the field lines is a function of the geographic latitude [1].

$$I=\mathrm{arctg}(2\mathrm{tg}(\varphi)) \qquad [1]$$

- where I is magnetic inclination, and φ - the geographic latitude. In addition, it is required that rocks are magnetized during their formation and that the magnetization acquired is parallel to the direction of the external field and proportional to its intensity. Thus, ideally, measuring the direction of a magnetization within a rock, will allow us to identify the locus (geographic latitude) of its formation (or acquisition of magnetization).

1. State of the art

During the last years paleomagnetic data has significantly improved our knowledge about the position of the major continents in the past (Fig.1). Nevertheless, data on the spatial and temporal evolution of many Paleozoic foldbelts remain patchy.

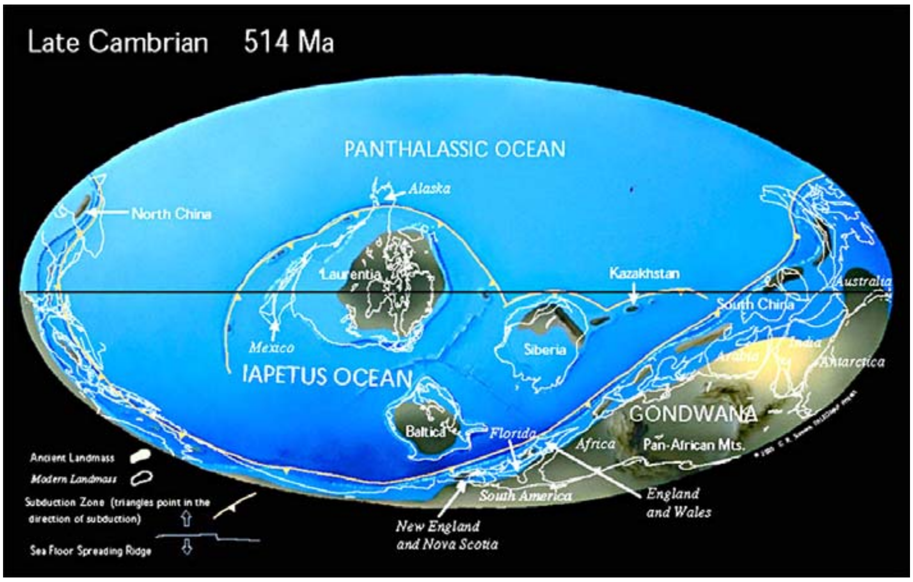


Figure 1. An example of global reconstruction for the Late Cambrian (http://www.scotese.com)

Today's foldbelts are made up of a variety of tectonic units which differ in age and the geodynamic setting they originate from and it is evident that the understanding of the interactions between these crustal elements provides the key to understanding how foldbelts evolve.

Adressing this fundamental issue – namely the evolution of foldbelts - a paleomagnetic study of Kazakhstan, a rather small element but a key area within the giant Ural - Mongolia folded belt, was carried out (Fig. 2).

The Paleozoic micro-continent of Kazakhstan is located in the central part of the Ural - Mongolia fold belt and is wedged between Baltica in the West, Siberia in the East, Tarim and Turan in the South. Unlike the surrounding paleocontinents, which are made up from pre-Cambrian continental crust, Kazakhstan represents a complex agglomerate of pre-Cambrian and Lower Paleozoic microcontinents and island arc terranes [Avdeyev, 1990; Yakubchuk, 1990; Sengör et al., 1993]. These smaller scale domains were amalgamated along numerous suture zones. Since amalgamation time Kazakhstan appears to have acted as a single block, which is supported by the spatial coherence of Devonian and younger formations [Apollonov, 2000; Filippova et al., 2001; Zaytsev, 1984; Zonenshain et al., 1990b].

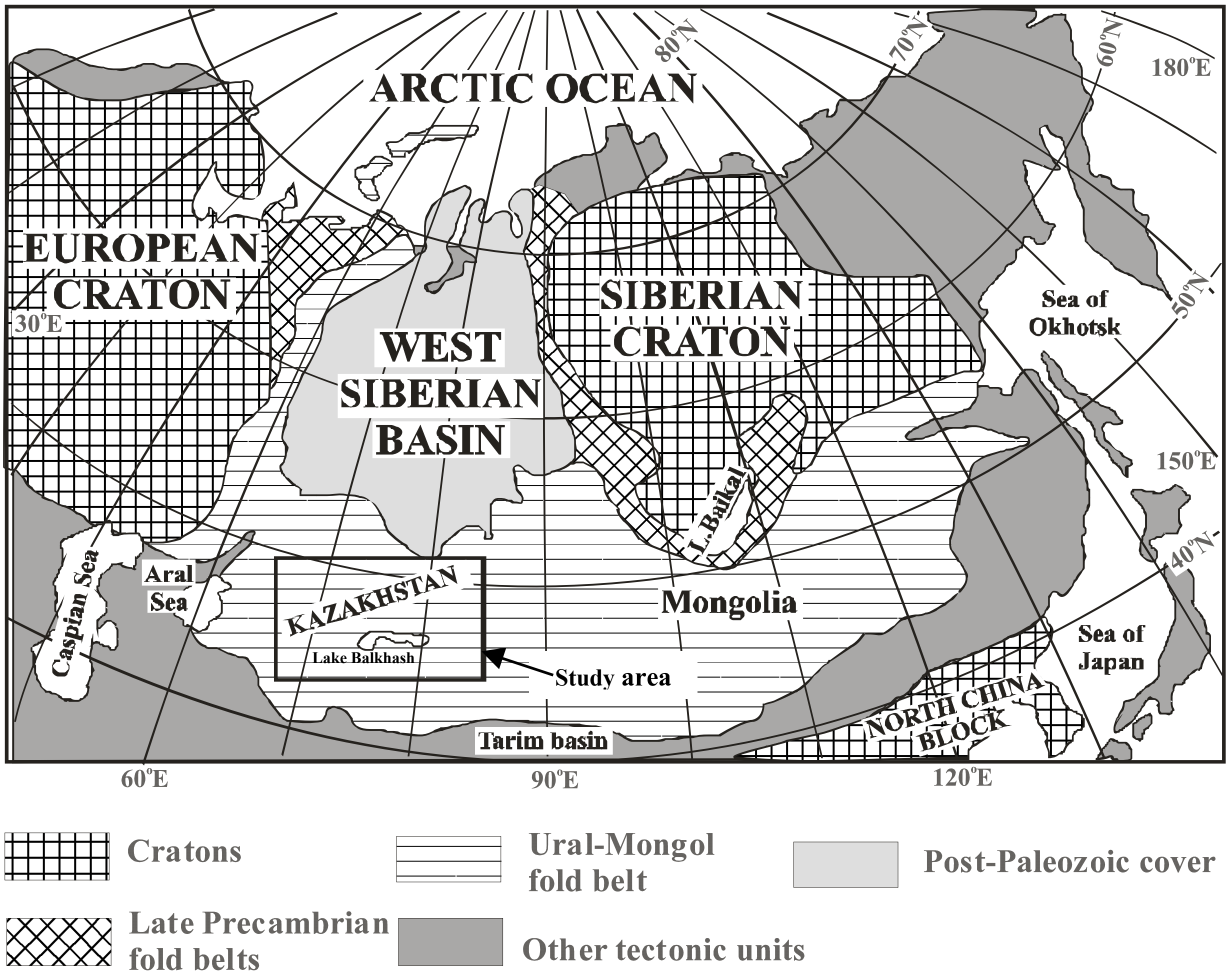


Figure 2. Location of the Ural-Mongol fold belt within Eurasia (after Collins et al. [2003]).

The most prominent tectonic features of the Paleozoic Kazakhstan are two volcanic belts of Devonian and Late Paleozoic age, which are bent into a giant horseshoe structure (Fig.3). From the Silurian through the Late Carboniferous the internal area of this loop-shaped structure was dominated by deeper marine facies and apparently connected to the deep marine Jungar basin in Northwest China. The outer parts of the horse shoe are marked by epicontinental shallow marine and continental deposits [Filippova et al., 2001; Zonenshain et al., 1990b].

Both Devonian and Upper Paleozoic volcanic belts are considered to have formed in an active continental margin setting, based on petrochemical, geochemical, and paleotectonic data

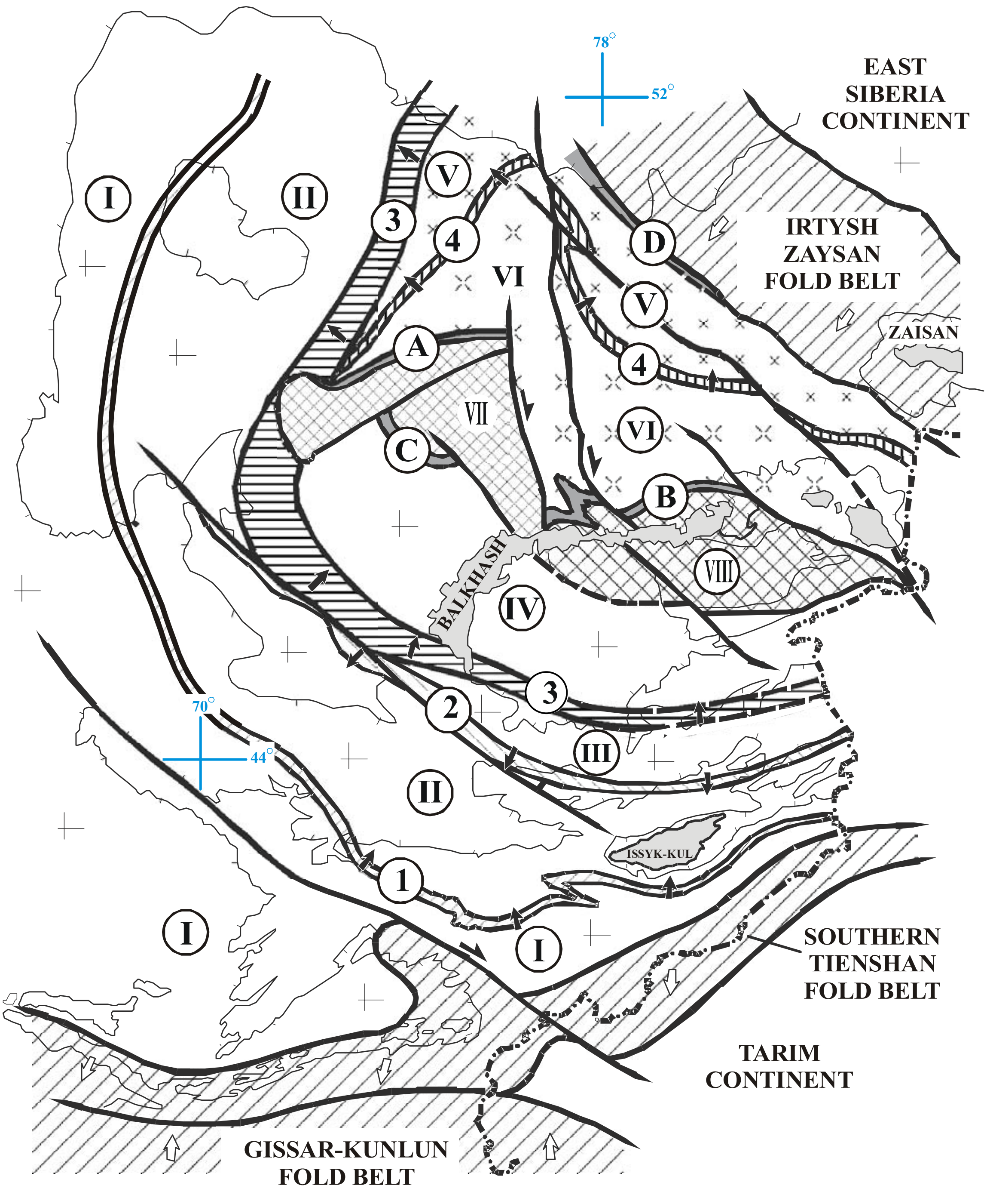


Figure 3. Main tectonic units of the Paleozoic of Kazakhstan (modified after Avdeyev and Kovalev [1989], and Yakubchuk [1990]). Legend see next page.

Allochthonous terranes:

Microcontinents with Lower Proterozoic continental crust
I - Kokchetav- Middle Tianshan

II - Stepnayk - Northern Tianshan

III – Zhel'tau; IV - Atasu-Junggar
Volcanic arcs with Lower Paleozoic simatic or heterogeneous basement

V - Boshchekul' - Chigiz arc

VI - Baydaulet - Akbastau arc

Middle and Upper Paleozoic accretionary complexes (Ages of main deformational events)

VII - Zhamansarysu block (Late Gevetian - Early Frasnian)

VIII - Balkhash block (Late Carboniferous - Early Permian)

Suture zones (Age of suturing and ophiolite emplacement)

1 - Ishim-Kirgiz-Terskey (Middle Arenigian)

2 - Zhalair-Nayman (Middle Arenigian)

3 - Eremen'tau - Yili (llandeilian and Cradocian in the North and Late Caradocian-Ashgillian in the South)

4 - Maykain-Akchatau (Ashgillian?- Middle Llandoverian)

- Marginal ophiolite zones

A - Tekturnas, B - Northern Balkhash, C - Agadyr', D - Arkalyk

- Late Paleozoic megasutures, bounding Kazakhstan

- major faults

Principal direction of collisional overthrusting

- within the Lower Paleozoic internal suture zones

- within the Upper Paleozoic external megasutures

- boundary of exposures. Short arrows are faced Mesozoic - Cenozoic cover

- CIS/China boundary

Figure 3. CTD. : Main tectonic units of the Paleozoic of Kazakhstan (modified after Zamaletdinov and Osmonbetov [1988], Avdeyev and Kavalev [1989], and Yakubchuk [1990]).

[Bakhteiev, 1987; Kurchavov, 1994; Skrinnik and Horst, 1995; Zonenshain et al., 1990b]. If this interpretation is correct, the subduction zone should be expected to be located in the central part of the volcanic loop. However the overall geometry of the structure, if primary, would make subduction from there rather unlikely. This implies that the curvature of the volcanic belt is, at least in parts, of secondary origin and can be interpreted as an orocline [Bazhenov et al., 2002; Levashova et al., 2003a; Weindl et al., 2002; Van der Voo et al., 2002; Zonenshain et al., 1990b].

Recognition of the possible oroclinal structure, quantification and dating of large scale rotations, reconstruction of the drift history of individual terranes and the drift history of Kazakhstan during the Paleozoic are among the principal goals of recent paleomagnetic studies conducted in this region. Despite the significant progress been made during the last years [Alexyutin et al., submitted; Bazhenov et al., 2002a; Bazhenov et al., 2003; Collins et al., 2003; Didenko and Morozov, 1999; Levashova et al., 2003a; Levashova et al., 2003b; Van der Voo et al., 2002; Weindl et al., 2002] the tectonic models, developed to explain the evolution of Kazakhstan during the Paleozoic still remain controversial and the data available are often insufficient to draw firm conclusions.

In order to provide new data which can be used to refine models for Paleozoic geodynamics of Kazakhstan, a paleomagnetic study in the Chu Yili and Kendyktas mountains of southern Kazakhstan, the central parts of Kazakhstan and the Chingiz range was undertaken.

2. A critical appraisal of the paleotectonic models for the evolution of Kazakhstan during Paleozoic time

A significant number of hypotheses related to the Paleozoic history of Kazakhstan have been developed over the past decade. Among the competing models, two general lines of thought can be identified. (a) Kazakhstan is a mosaic of microplates and island arcs amalgamated by the latest Ordovician and positioned in low northerly latitudes throughout the Paleozoic [Didenko et al., 1994] (Fig. 4) or (b) Kazakhstan was formed by continuous accretion of volcanic arcs along the Kipchak Arc moving from a southerly position into northern latitudes throughout the Paleozoic [Sengör and Natal'in, 1996] (Fig 5). Both, Sengör and Natal'in, [1996] and Didenko et al., [1994] reconstructed a volcanic arc, subparallel to a meridian along the eastern part of Baltica - Siberia during the Early Paleozoic. But the question, whether Kazakhstan (as well as some another tectonic units) actually formed part of this arc is still open. Due to the scarcity of reliable paleomagnetic data, the identification of terranes now integrated into Kazakhstan is difficult and the reconstruction of their drift history still remains rather patchy.

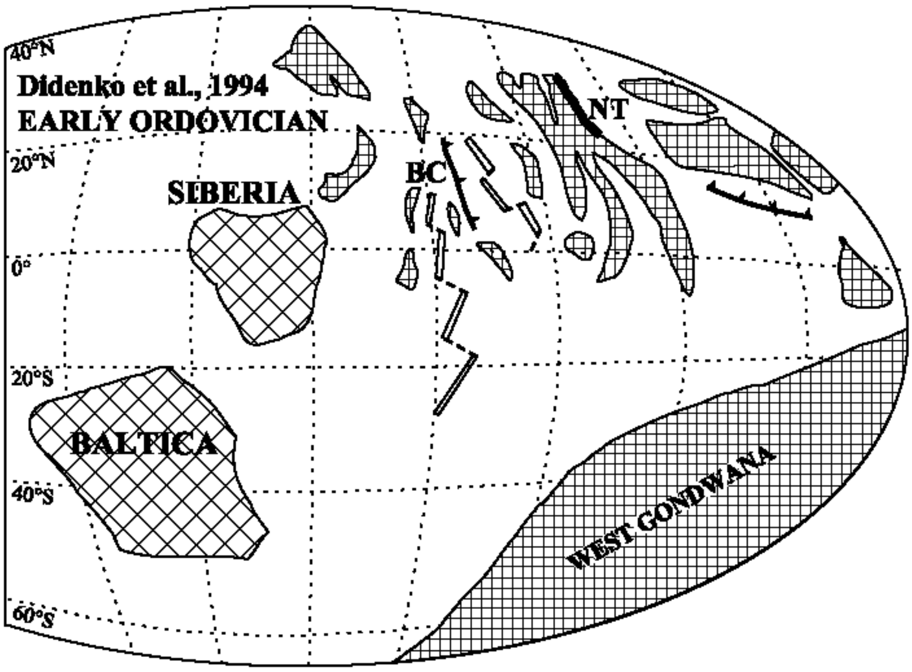


Figure 4. Palinspastic reconstructions of the Ural–Mongol belt according to Didenko et al., [1994]. BC - Boshekul Chingiz volcanic arc, NT - North Tien Shan block.

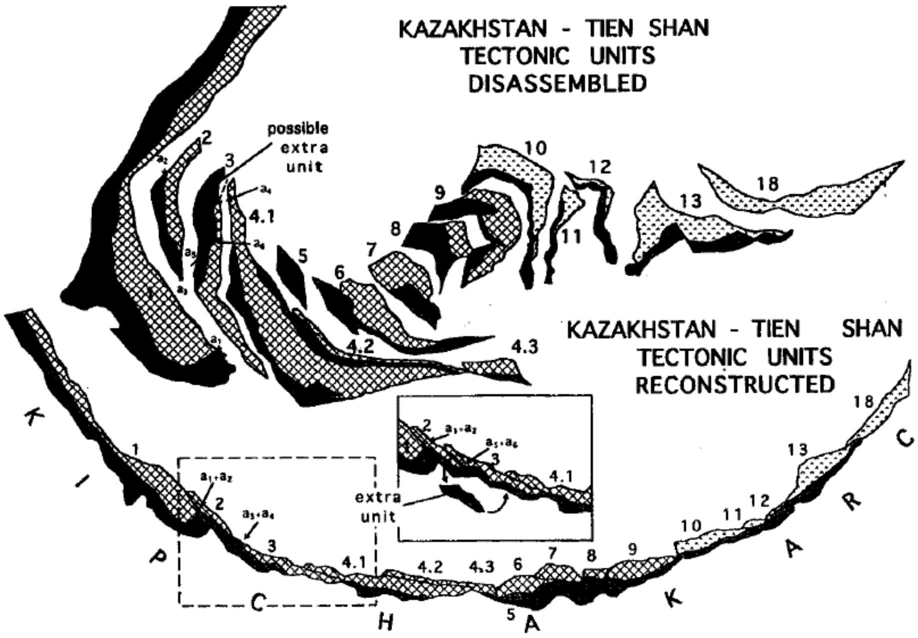


Figure 5. Principe of palinspastic reconstructions of the Ural–Mongol belt taken from Sengör and Natal'in, [1996]. 1 - Valerianov-Chatkal complex; 2 - Turgay complexes; 3 - Baykonur-Talas complexes; 4.1 - Djezkazgan-Kirgiz complexes; 4.2 - Jalair-Naiman complexes; 4.3 or 16 - Borotala complexes; 5 - Sarysu complexes; 6 - Atasu-Mointy complexes; 7 - Tengiz complexes;

8 - Kalmyk-Kokchetav complexes; 9 - Ishim-Stepnyak complexes; 10 - Ishkeolmes complexes; 11 - Selety complexes; 12 - Akdym complexes; 13 - Boshchekul-Tarbagatay complexes; 14 - Tekturmas complexes; 15 - Junggar-Balkhash complexes; 17 - Tar-Muromtsev complexes; 18 - Zharma-Saur complexes.

3. Methodology

Classic paleomagnetic methods were used for this study. Lower Ordovician to Permian rocks were sampled within the main tectonic units of Kazakhstan. Only macroscopically fresh-looking rocks with well-constrained ages (by biostratigraphic or absolute age methods) and unambiguous tectonic setting were considered suitable for sampling. All selected sections are characterized by the varying bedding attitudes, thus giving ample opportunity for the application of fold tests [Enkin, 2003].

Each section studied has been sampled at 5 to 13 sites (5-7 cores each site). All samples (one inch in diameter) have been taken using a gasoline powered drill and oriented using a standard magnetic compass. One (sometimes two) specimen from each core were subjected to stepwise thermal demagnetization in 15 to 30 steps up to 690°C in magnetically shielded Schonstedt or ASC-scientific ovens and measured with a 2G cryogenic magnetometer. All equipment used is housed in a magnetically shielded room in the Geophysics Section of the Department for Earth and Environmental Sciences, Ludwig-Maximilians Universität (LMU), München (Neiderlippach). Demagnetization results were analyzed using orthogonal vector diagrams [Zijderveld, 1967; Kirschvink, 1980]. Magnetization components were identified by eye and subjected to principal component analysis using a standard analysis package by R. Enkin (http://www.pgc.nrcan.gc.ca/people/renkin_e.php). The characteristic sample directions were averaged into site means, and then tested, using foldtests. Finally, paleomagnetic declinations and inclinations, as well as ages of magnetic components (obtained as results of the foldtest), were used for paleotectonic reconstructions. Here, “GMAP” by Trond Torswik has been used (http://www.ngu.no/dragon).

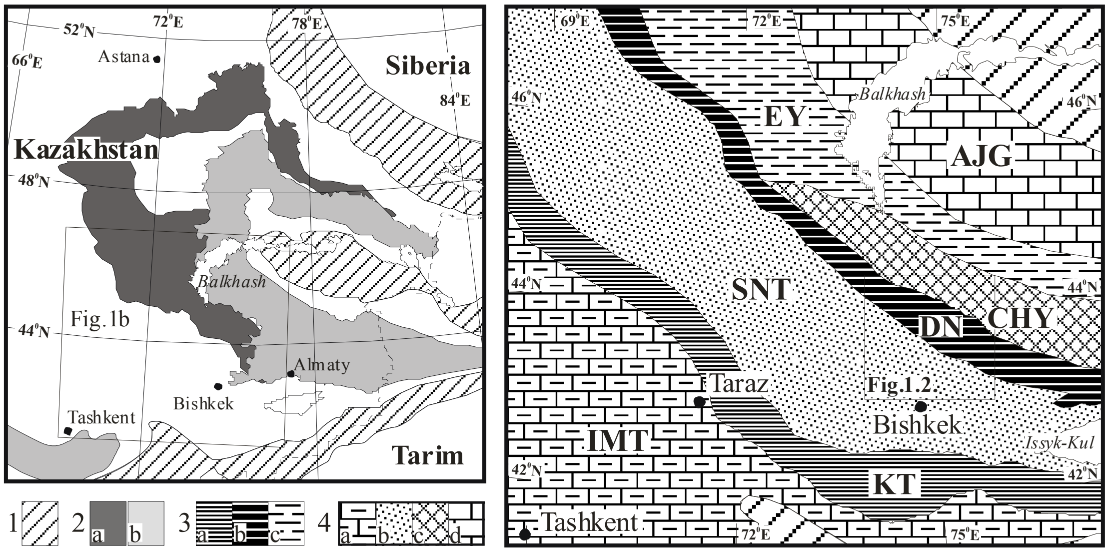
Part 1

Paleomagnetism of Ordovician and Silurian rocks from the Chu-Yili and Kendyktas mountains, South Kazakhstan

1.1. Tectonic setting

The Lower Paleozoic basement of Southern Kazakhstan and the Northern Tian Shan comprises four microcontinents, which are separated one from another by tectonic suture zones (Fig. 1.1). The microcontinents - Ishim-Middle Tian-Shan (IMT), Stepnyak-North Tian-Shan (SNT), Chu-Yili (CHY) and Atasu-Junggar (AJG) can be identified as elongated blocks within the Lower Proterozoic crystalline basement and the Upper Proterozoic and/or Lower Paleozoic sedimentary cover. The suture zones - Kyrgyz-Terskey (KT), Dzhalair-Nayman (DN), and Erementau - Yili (EY) – are marked by Lower Paleozoic ophiolites and/or deeper marine sediments. Within the KT suture the rocks range in age from the Early Cambrian to Mid Arenigian; in the DN suture - from early Cambrian (?) to Tremadocian, and in YE suture zone they embrace the Middle Cambrian to Caradocian [Apollonov, 2000; Avdeyev and Kovalev, 1989; Mikolaichuk et al., 1997; Nikitin and Nikitina, 2000].

The DN and KT suture zones mark the amalgamation of the SNT, CHY, and apparently IMT microcontinents during the Early and the Middle of the Arenigian, respectively [Avdeyev, 1990; Mikolaichuk et al., 1997]. During Late Arenigian and Llanvirnian times, passive margin deposits dominate the sedimentary record of this composite microcontinent. From the Llandeilian onward up to the Ashgillian the tectonic setting of this terrane changes and the Stepnyak-North Tian Shan volcanic arc evolves above a southwest-dipping (today’s coordinates) subduction zone. The volcanic arc is located mainly within the former SNT and KT tectonic



a) b)

Figure 1.1. Tectonic setting of Upper Paleozoic Kazakhstan (a) and Lower Paleozoic South Kazakhstan and North Tian-Shan (b). 1 - Upper Paleozoic thrust folded belts; 2- Subductional (?) volcanic belts: a) Lower and Middle Devonian, and b) Carboniferous and Permian; 3 - Lower Paleozoic suture zones: a) Kyrgyz -Terskey (KT), b) Dzhalair - Naiman (DN), and c) Erementau - Yili (EY); 4 - Microcontinents: a) Ishim - Middle Tian-Shan (IMT), b) Stepnyak - Northern Tian- Shan (SNT), c) Chu-Yili (CHY), d) Atasu - Junggar (AJG)

domains, whereas the fore-arc basin includes the former CHY and DN terranes [Apollonov, 2000; Apollonov and Patalakha, 1989; Mikolaichuk et al., 1997]. The EY deeper marine basin developed from Cambrian through the late Ordovician and was eliminated due to the collision of the Atasu-Junggar microcontinent with the Stepnyak-North Tian Shan arc [Apollonov, 2000]. As a result of this collision the activity of the volcanic arc ceased, and almost the entire area from AJG to IMT experienced substantial deformation and granite batholiths were emplaced along the whole length of the former arc. However, significant deformation did not occur in the Chu-Yili area, where sedimentation continued until the late Silurian.

1.2. Geology and sampling

A paleomagnetic study has been conducted in the Kendyktas ridge and in the south of the Chu-Yili Mountains (Fig 1.2). The sampled first area is a part of the Stepnyak-North Tian-Shan facies zone of Ordovician age [Nikitin, 1972]. The second belongs to the Selety-Chu-Yili facies zone of Ordovician and Silurian ages [Bandaletov, 1969; Nikitin, 1972]. A detailed description of the Paleozoic stratigraphy of these areas is given in a number of publications [Keller and Rukavishnikova, 1961; Nikitin, 1972; Popov et al., 2001] and is only summarized here.

In the Kendyktas ridge the Lower Paleozoic rocks range from late Cambrian to Ashgillian age. Late Cambrian and early Ordovician rocks are exposed in the south of the ridge with the best sections located on the banks of Agalatas river (Fig. 1.2a, area 1). The section is subdivided into three formations, which are dominated by shallow marine deposits [Popov et al., 2001; Rukavishnikova and Salin, 1965]. They consist, from bottom to top, of brown, green, and gray sandstones and siltstones (*Kendyktas formation*, Upper Cambrian and Lower Tremadocian), light-colored massive thick-bedded fossiliferous limestone (*Agalatas formation*, Upper Tremadocian) and red-pink and violet sandstones, siltstones and limestones (*Kurday formation*, lower Arenigian).

Rocks of Upper Arenigian, Middle and Upper Ordovician ages are well exposed on the southwestern slopes of Kendyktas (Fig. 1.2b). Here, the *Shcherbakty formation* (Upper Arenigian and Llanvirnian) consists of green and gray-colored argillites, sandstones, and shales, which were accumulated in a passive margin depositional setting. The overlying formations were formed within an ensialic volcanic arc [Nikitin et al., 1991]. The *Rgaity formation* (Llandeilian and lower Caradocian) consists of shales, tuffs and intermediate volcanic rocks in the lower part of the section. It is dominated by red-colored massive and cross-bedded sandstones and siltstones (about 850 meters thick) in the upper part. The *Keskintas formation* (Upper Caradocian) comprises andesitic and basaltic porphyrites, tuffs, green sandstones, limestones and conglomerates. Up-section the lithology changes into the brown and green conglomerates, sandstones and siltstones of the *Taspaly formation,* which were dated tentatively as Upper Ordovician in age [Nikitin, 1972].

Two early Paleozoic deformational events of mid Arenigian and late Ordovician ages can be identified in the Kendyktas ridge. The mid Arenigian event, coeval with an episode of suturing within the KT zone, resulted in the Kendyktas ridge only in a low-angle unconformity without major deformation. The main deformation occurred in the Late Ordovician and is related to the collision of the AJG microcontinent with the Stepnyak North Tian Shan volcanic arc. The Upper Cambrian up to Upper Ordovician rocks were heavily folded with northwest-southeast striking fold axis, and later cut by granite batholites. Late Ordovician age was assigned to these events. This assumption is based on the fact that the youngest rocks affected by folding are of Late Ordovician in age, and that the granite batholites, cutting the folds are Late Ordovician and Silurian age [Mikolaichuk et al., 1997; Myasnikov et al., 1979].

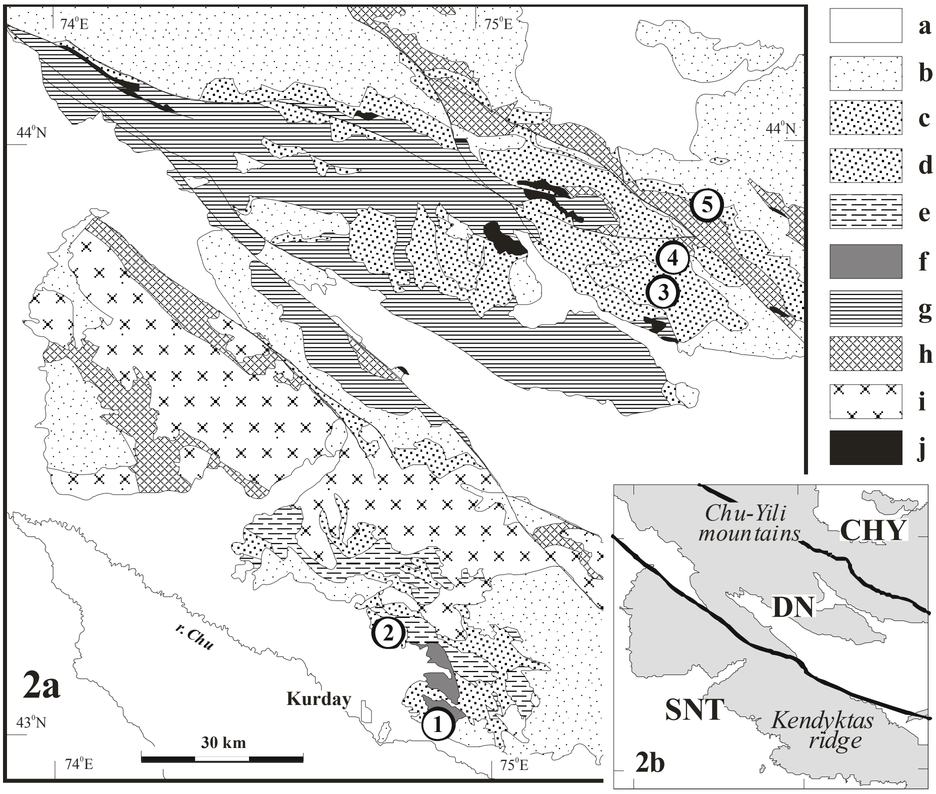


Figure 1.2. Schematic geological map of the South Chu-Yili and Kendyktas mountains (2a); orographic and structural units (2b). a - Cenozoic, b - Devonian and Upper Paleozoic, c - Silurian, d - Middle and Upper Ordovician, e - Lower and Middle Ordovician, f - Lower Ordovician, g - Cambrian and Lower Ordovician, h - Proterozoic, i - Upper Ordovician granites, j - Ophiolites

Numbers in circles show sampling areas: 1 - Agalatas river (AGA), 2 - Georgievka (GEO), 3 and 4 - Dulankara mountains: 3 - sites DUL 1-8; and 4 - sites DUL 9-11, 15-19; 5) Anderkenyn - Akchoku ravine (AND).

Abbreviations: SNT - Stepnyak North Tian Shan microcontinent, CHY - Chu-Yili microcontinent, DN - Dzhalair-Naiman suture zone.

In the Chu-Yili mountains the Lower Paleozoic formations can be clearly divided into two complexes. The lower one developed within the DN suture zone and comprises Cambrian to Tremadocian ophiolites and deep marine sediments. These rocks are typically intensively deformed and metamorphosed. The upper complex comprises predominantly siliciclastic rocks, which range in age from the Arenigian through the Silurian. They unconformably overlay both the Cambrian and Lower Ordovician rocks of the DN suture and the Lower Proterozoic crystalline schists within the CHY microcontinent.

The Arenigian and Llanvirnian comprise shallow marine siliciclastic rocks, which contain minor amounts of andesites in the Arenigian stage. Llandeilian, Caradocian and lower Ashgillian rocks are presented by a broad variety of siliciclastic rocks, ranging from non-marine and shallow marine to deeper marine turbidite facies [Popov et al., 2001]. These deposits are interpreted to have been formed in the fore-arc basin of the Stepnyak-North Tian Shan arc [Apollonov, 2000].

The uppermost Ordovician and Silurian formations were accumulated in a nearshore part of the Junggar - Balkhash basin, which was situated northeast of the Chu-Yili. The Ashgillian and lower Llandowerian (*Dzhalair and Salamat formations*) consist of green- and gray-colored marine sandstones, siltstones, and argillites. They are disconformably overlain by light-colored massive and cross-bedded quartz-rich sandstones and conglomerates of the lower Silurian *Betkainar formation*. The last one changes up-section into the red-colored sandstones and siltstones of the *Koiche formation*. The Early Silurian age of *Koiche* formation is based on brachiopods collected from limestone strata in the lower part of formation.

The *Koiche* formation is overlain by non-marine red-colored sandstones and conglomerates, conditionally dated as late Silurian - early Devonian [Abdulin et al., 1980; Bandaletov, 1969]. Occasionally, a minor low angle unconformity (5 - 15°) between Late Silurian and Early Devonian rocks can be identified in several localities in the Chu-Yili mountains. This, however, is the exception and generally the Silurian, Lower and Middle Devonian rocks seem to have been deformed conformably and form coherent fold structures. These folds are cut by granite intrusions of Late Givetian and Frasnian age bracketing the time of folding to be Givetian [Abdulin (Ed.) et al., 1980].

Paleomagnetic samples in the Kendyktas region were collected from the lower parts of the Kurday formation (Lower Arenigian) along the Agalatas river some 15 km east of Kurday (Fig. 1.2 area 1 – locality AGA), and from the Llandeilian and Caradocian red beds of the Rgaity formation 20 km to the north of Kurday (Fig. 1.2 area 2 – locality GEO).

In the south Chu-Yili region paleomagnetic sampling was focused on the Dulankara mountains and the Anderkenyn-Akchoku ravine. The samples were taken from red sandstones of the Lower Silurian Koiche formation (Fig. 1.2 area 3 – sites DUL 2-8; area 4 – sites DUL 15-19), and from the upper Silurian and lower Devonian sandstones (Fig. 1.2 area 4 sites DUL 9-11; area 5 - locality AND).

1.3. Results

The directional characteristics of almost all samples are controlled by the presence of two distinguishable components of magnetization.

Component A is based on at least four consecutive demagnetization steps (Fig. 1.3a). Component A is normally removed during stepwise heating at temperatures of up to 540°C and is characterized by intermediate to steep upward pointing inclinations and declinations between 215 and 355° in geographic coordinates (Fig. 1.3). Only occasionally the maximum unblocking temperatures are in excess of 580°C indicating that in addition to magnetite, hematite might also be carrier of this magnetization. Although the majority of component A is of single (reversed) polarity, we note that in samples from localities DUL and AND normal and reverse directions of component A can be observed. Component A fails the foldtest and is clearly of secondary origin. Significant differences in declination and inclination as well as the occurrence of normal and reversed polarity can be used to argue against a short time interval of remagnetization. It is, therefore, argued that the various units have been remagnetized at different points in time.

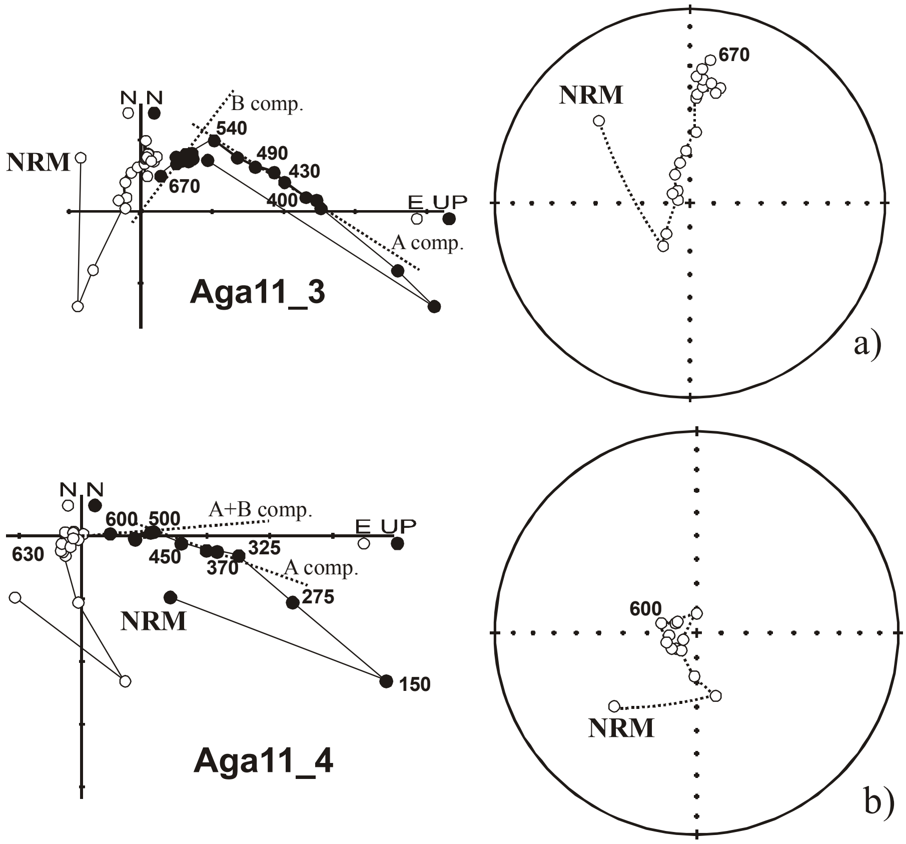


Figure 1.3. Orthogonal plots of thermal demagnetization data. Temperatures are in °C. Stratigraphic coordinates. On stereograms - open (solid) symbols - upper (lower) hemisphere.

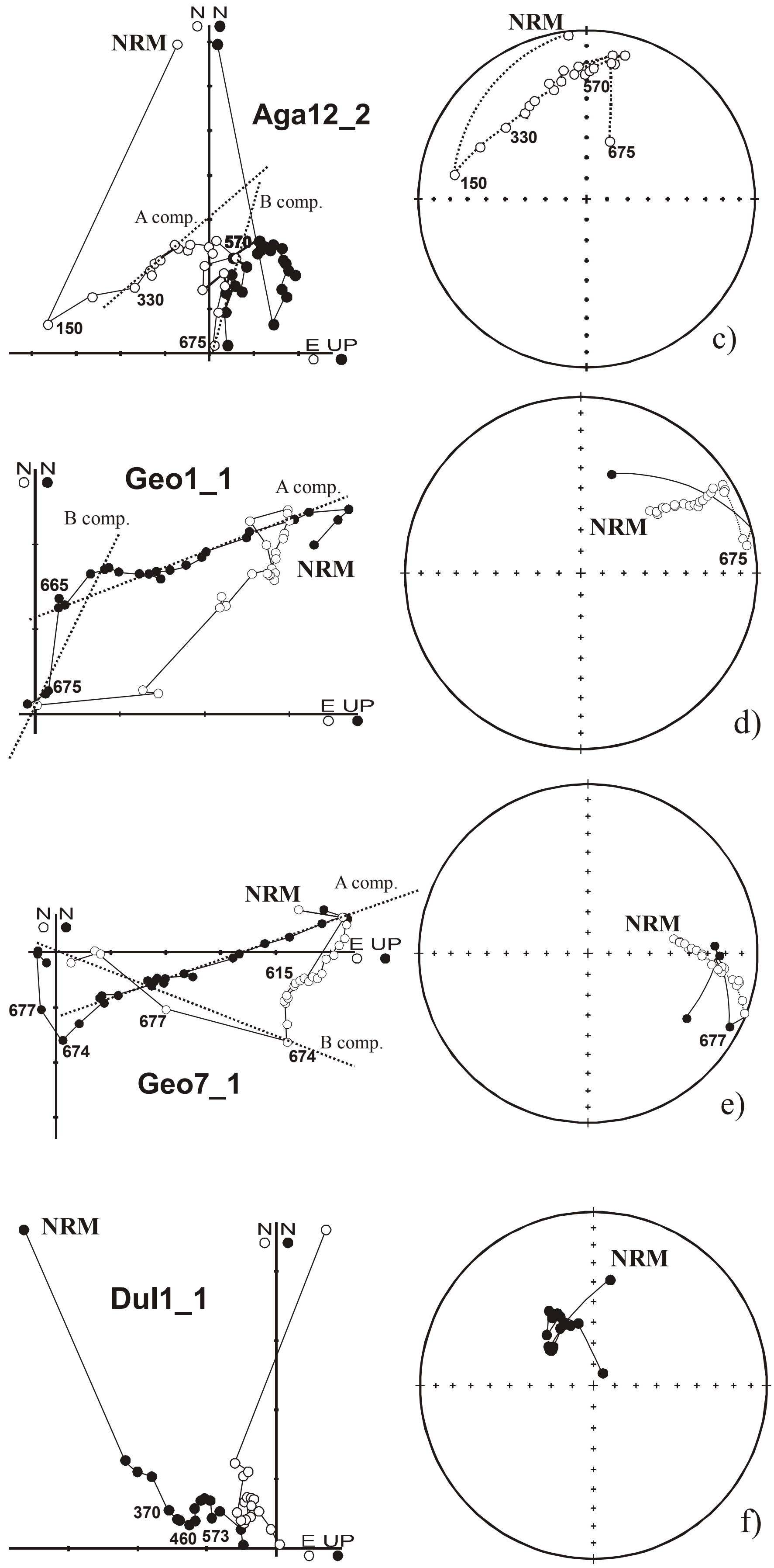


Figure 1.3. CTD.: Orthogonal plots of thermal demagnetization data.

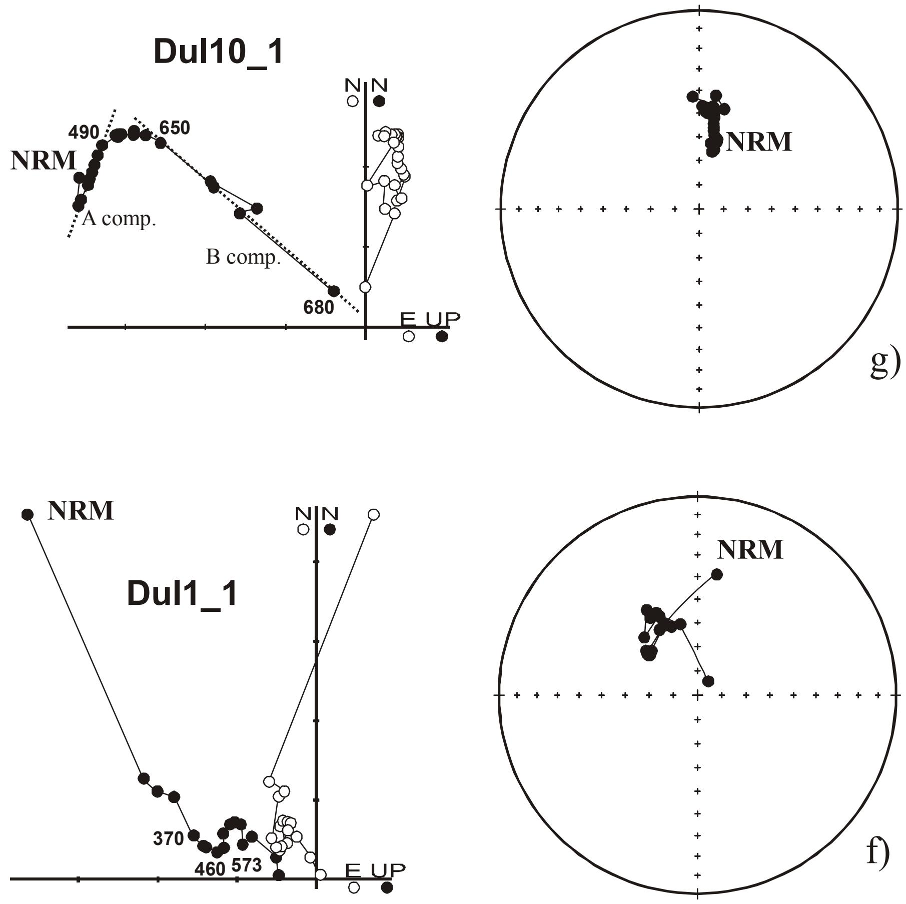


Figure 1.3. CTD.: Orthogonal plots of thermal demagnetization data.

Component B identified in Lower Ordovician rocks (Kendyktas area) sometimes displays very narrow unblocking temperature spectra (about 5°C) and can usually be isolated in the temperature interval 580 – 680° C (Fig. 1.3c), indicating hematite to be the carrier of the remanent magnetization. In several samples the high temperature component shows a close similarity to the direction of component A (Fig. 1.3b). The distribution of component B significantly improves upon tilt correction and passes the fold test. The resulting mean direction (D= 9.2°, I=-16.9°, k=26.9, α_{95}=15.0°) is, therefore, considered as being pre-folding in age. The age of folding in the Agalatas area is defined as Late Ordovician (see geological description). Based on the negative fold test, a post deformational age, i.e. post Late Ordovician can be assumed for component A, whereas the positive result of the fold test for component B demonstrates that this component is unambiguously of pre-folding age. It is very likely to have been acquired during the Early to Late Ordovician.

Component B for the Silurian – Early Devonian rocks (Chu-Yili area) was isolated in the temperature interval of 580 – 680° C (Fig. 1.4a), again as above, indicating hematite to be the carrier. The grouping of the site-mean directions of component B improves significantly upon

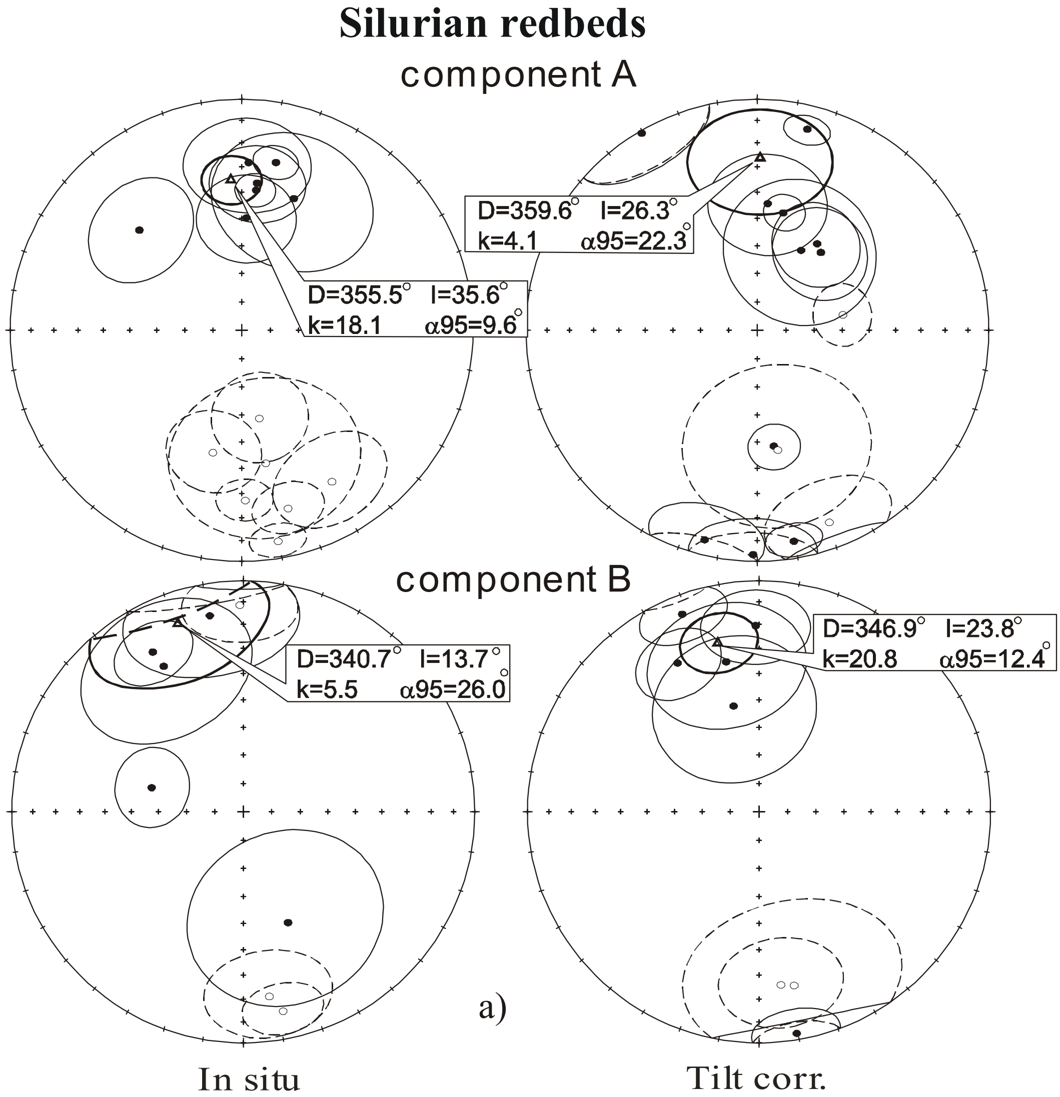


Figure 1.4 a. Site-mean directions and α95 confidence circles. Open (solid) symbols - upper (lower) hemisphere. The mean directions are listed in Table 1.

stratigraphic correction and passes the fold test on the 95% confidence level. The resulting direction (D= 346.9°, I=23.8°, k=20.8, α95=12.4°) is therefore of pre-folding origin.

Based on the positive fold test, component B is interpreted to be pre-folding in origin, and thus predates the mid Devonian deformational event.

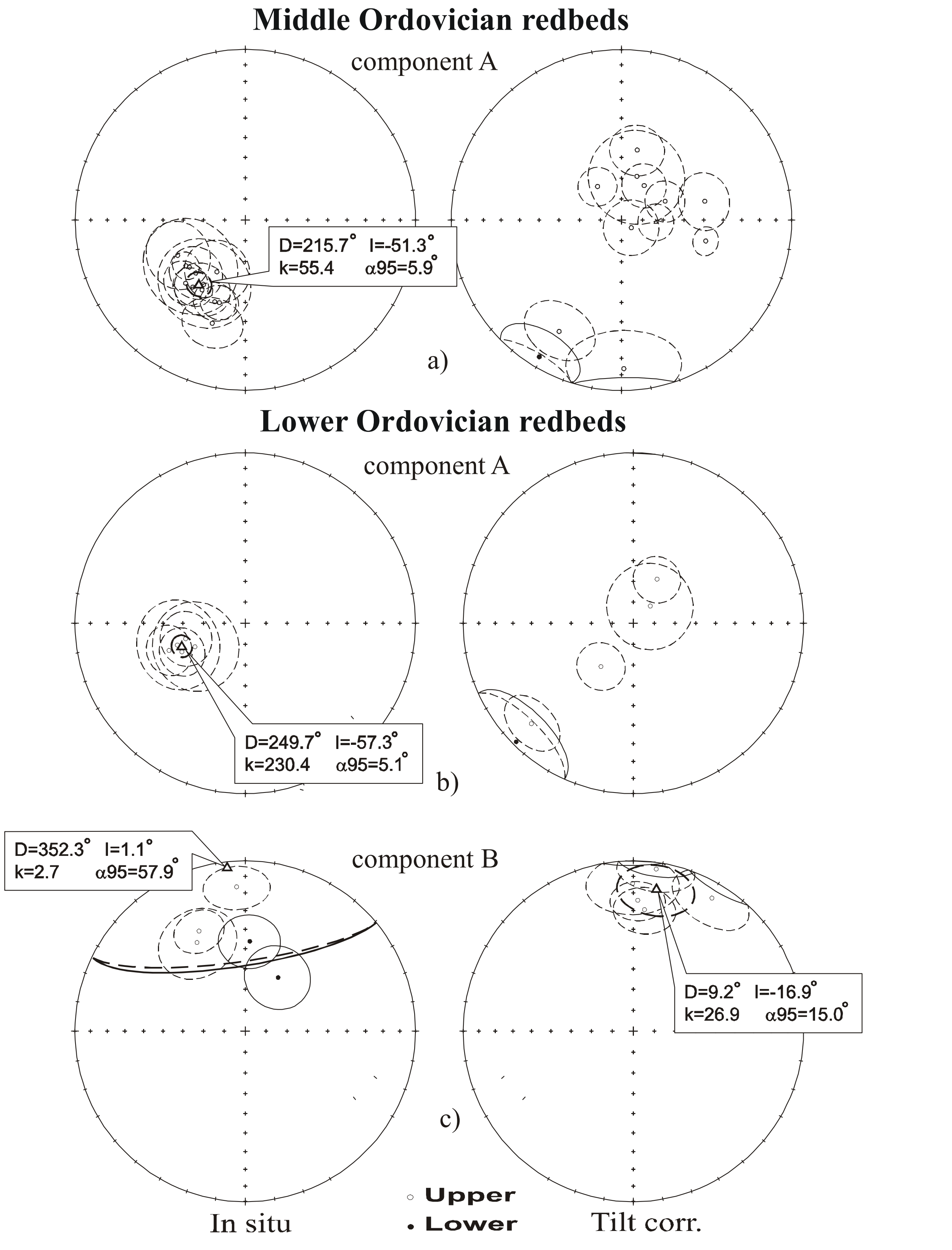


Figure 1.4 a,b,c. Site-mean directions and α95 confidence circles. Open (solid) symbols - upper (lower) hemisphere. The mean directions are listed in Table 1.1.

Table 1.1. Site – mean directions of sites AGA, GEO, DUL, and AND.

Site	Number of specimens	In situ				Tilt.corrected			
		D [°]	I [°]	k	α_{95} [°]	D [°]	I [°]	k	α_{95} [°]
Lower Ordovician (locality AGA)									
Component A									
AGA 9	6	245.5	-56.4	36.7	11.2	28.4	-66.2	36.7	11.2
AGA 10	6	252.0	-55.5	11.5	20.7	44.7	-78.6	11.5	20.7
AGA 11	6	250.3	-50.7	34.2	11.6	216.3	-63.9	35.1	11.5
AGA 12	6	255.3	-60.3	28.8	12.7	225.4	-16.9	28.7	12.7
AGA 13	5	244.7	-63.3	14.1	21.1	224.8	2.4	14.1	21.1
mean		**249.7**	**-57.3**	**230.4**	**5.1**	**226.8**	**-59.3**	**2.7**	**57.3**
Component B									
AGA 9	6	331.4	-40.5	12.6	17.7	359.7	-14.5	12.6	17.7
AGA 10	4	335.1	-35.6	69.6	11.1	1.9	-24.3	69.6	11.1
AGA 11	4	356.5	-16.6	123.1	8.3	5.2	-29.2	51.9	12.9
AGA 12	6	2.7	46.0	24.7	13.8	8.0	-4.6	24.7	13.8
AGA 13	5	31.1	59.6	25.4	15.5	30.6	-10.6	25.4	15.5
mean		**352.3**	**1.1**	**2.7**	**57.9**	**9.2**	**-16.9**	**26.9**	**15.0**
Middle Ordovician (locality GEO)									
Component A									
GEO 1	6	223.2	-47.5	40.9	10.6	33.6	-70.4	40.9	10.6
GEO 2	6	197.5	-47.6	60.3	8.7	93.9	-73.5	60.3	8.7
GEO 3	4	218.0	-48.3	98.7	9.2	324.1	-70.4	98.7	9.2
GEO 5	5	197.8	-36.3	34.0	13.3	129.0	-84.0	34.0	13.3
GEO 6	4	223.0	-54.7	53.9	12.6	12.7	-55.5	53.9	12.6
GEO 7	7	200.6	-47.3	39.9	9.7	67.1	-67.3	39.9	9.7
GEO 9	3	208.7	-61.3	65.9	15.3	209.2	-25.8	65.9	15.3
GEO 10	4	212.9	-52.6	25.8	18.5	179.1	-13.6	18.7	21.8
GEO 14	4	242.1	-52.8	34.9	15.8	211.2	7.0	34.9	15.8
GEO 16	6	211.8	-49.9	27.7	13.0	77.5	-48.5	27.7	13.0
GEO 16-1	6	229.7	-54.4	9.6	22.8	19.6	-68.0	9.6	22.8
GEO 17	6	232.3	-53.5	106.9	6.5	104.2	-47.6	106.9	6.5
mean		**215.7**	**-51.3**	**55.4**	**5.9**	**130.0**	**-78.6**	**3.4**	**28.1**

Silurian and Lower Devonian (localities DUL and AND)									
Component A									
DUL 2	7	2.4	49.7	14.4	16.5	39.3	54.5	14.4	16.5
DUL 3	4	6.2	36.1	37.5	15.2	34.5	52.7	37.5	15.2
DUL 5	3	2.0	28.5	41.5	19.4	4.7	44.0	41.5	19.4
DUL 6	7	11.5	26.7	77.9	6.9	12.9	46.6	77.9	6.9
DUL 7	5	21.6	38.6	9.3	26.4	28.5	57.6	9.3	26.4
DUL 8	6	169.7	-41.2	5.6	31.2	170.5	-46.1	5.6	31.2
DUL 9	6	192.9	-44.7	19.3	15.6	193.8	7.3	19.3	15.6
DUL 10	6	168.2	-58.0	17.4	16.5	181.1	3.1	17.4	16.5
DUL 11	4	179.0	-27.2	115.5	8.6	171.8	47.6	115.5	8.6
DUL 15	5	170.2	-8.4	99.1	7.7	170.1	8.5	99.1	7.7
DUL 16	5	149.4	-24.8	18.9	18.1	159.5	-12.3	18.9	18.1
DUL 17	3	5.6	38.9	359.6	6.5	13.9	11.6	359.6	6.5
DUL 18	6	165.3	-21.4	40.0	10.7	79.7	-59.3	40.0	10.7
AND 4	5	314.9	37.8	18.5	18.3	329.6	0.5	18.5	18.3
mean		**355.5**	**35.6**	**18.1**	**9.6**	**359.6**	**26.3**	**4.1**	**22.3**
Component B									
DUL 2	7	331.3	29.0	5.8	27.5	346.5	51.2	5.8	27.5
DUL 4	5	359.0	-11.6	24.2	15.9	358.9	20.4	24.2	15.9
DUL 7	4	350.4	15.0	14.5	25.0	347.5	34.0	14.5	25.0
DUL 8	6	172.2	-20.4	13.7	18.7	172.7	-25.3	13.7	18.7
DUL 15	5	168.6	-13.7	45.9	11.4	170.5	3.0	45.9	11.4
DUL 16	6	330.5	21.7	30.8	12.3	338.9	9.1	30.8	12.3
DUL 18	6	158.4	47.2	5.1	33.0	168.6	-24.2	5.1	33.0
AND 4	6	285.0	56.3	25.2	13.6	331.4	27.5	25.2	13.6
mean		**340.7**	**13.7**	**5.5**	**26.0**	**346.9**	**23.8**	**20.8**	**12.4**

D - declination; I - inclination; k - precision parameter; α_{95} - radius of confidence circle (Fisher, 1953).

Table. 1.2. Obtained directions and virtual geomagnetic pole positions.

Locality	Age of rocks	Loc. Lat. [°N]	Loc. Long. [°E]	D [°]	I [°]	k	α95 [°]	Pol. Lat [°]	Pol. Long [°]	dp/dn [°]	φ [°]	Age of magnetization
DUL and **AND**	**Silurian and Lower Devonian** (Postfolding comp.)	**43°48'**	**75°28'**	**355.5**	**35.6**	**18.1**	**9.6**	**65.6**	**265.8**	**6.4/11.1**	**19.7 +7.3/-6**	**post Middle Devonian**
DUL and **AND**	**Silurian and Lower Devonian** (Prefolding comp.)	**43°48'**	**75°28'**	**346.9**	**23.8**	**20.8**	**12.4**	**56.7**	**279.3**	**7.1/13.4**	**12.4 +7.7/-6.6**	**Silurian to Early Devonian**
GEO	**Middle Ordovician**	**43°10'**	**74°53'**	**215.7**	**-51.3**	**55.4**	**5.9**	**59.8**	**174.6**	**5.4/8.0**	**32.0 +5.8/-5.1**	**post Late Ordovician**
AGA	**Lower Ordovician** (Postfolding comp.)	**43°02'**	**74°54'**	**249.7**	**-57.3**	**230.4**	**5.1**	**38.3**	**145.3**	**5.4/7.4**	**37.9 +5.8/-5.1**	**post Late Ordovician**
AGA	**Lower Ordovician** (Prefolding comp.)	**43°02'**	**74°54'**	**9.2**	**-16.9**	**26.9**	**15.0**	**37.7**	**243.3**	**8.0/15.5**	**-8.6 –8.7/+7.6**	**Early to Late Ordovician**

Loc. Lat. and Loc. Long – the locality position; D - declination; I - inclination; k - precision parameter (Fisher, 1953); A95 - radius of confidence circle. Pol. Lat, Pol. Long and dp/dn are the latitude, longitude, and radius of 95% confidence circle of the paleopole, respectively; φ - paleolatitude.

1.4. Paleogeographic implication

The results summarized in the previous chapter allow to make important conclusions about the paleogeographic history of Kazakhstan.

Component B, isolated in rocks of Arenigian age in the Agalatas area passes the fold test and therefore has to be considered to have been acquired during or shortly after deposition. The resulting paleolatitude for component B, based on a mean direction of 9° declination) and of –17° (inclination), puts the SNT into a southerly paleolatitude of 9° ± 9° if the normal polarity option is chosen. This result is in agreement with both the data obtained for the Middle and Upper Ordovician rocks in the Northern Tian Shan [Bazhenov et al., 2003] (Fig. 1.5), and with the data available for Ordovician ophiolites in Central Kazakhstan [Grishin et al., 1997] all reporting northerly declinations for presumably Ordovician magnetizations. If these results are correct, they imply no major rotations between the North Tian Shan, including the Agalatas area and Central Kazakhstan since the Ordovician. However, the quality of the data from Central Kazakhstan remains questionable (Fig. 1.6). The age of magnetization is not well constraint and it is rather debatable to what extent paleomagnetic data from ophiolites can be taken as being representative for microcontinents and/or terranes.

The pre-folding component of magnetization isolated in the Silurian and Lower Devonian rocks in the South Chu-Yili mountains shows a northerly declination and positive inclination (D = 346.9°, I =23.8°) and indicates a northerly paleolatitude of the area of 12.4° ± 7.7° if again a normal polarity is assumed. This result, however, is in sharp contrast to other data published earlier for Silurian and Devonian rocks in Central Kazakhstan [Grishin et al., 1997]. These show southerly declinations, which differ from the results of this study by up to 150°. However, this cannot be taken as evidence for oroclinal bending. The area to the northwest of Balkhash, where a pre-folding magnetization of Devonian age (D = 319°, I = -52°, [Grishin et al., 1997]) has been reported, and the Chu-Yili mountains are located within a structurally continuous belt with uniform strike. Therefore, major rotations seem unlikely. In addition, the fact that the Ordovician directions for Central Kazakhstan and the Northern Tien Shan agree is a strong argument against major oroclinal bending. Nevertheless, more high quality data is urgently needed before this matter can be finally decided.

Ordovician magnetizations from the Chingiz Range (North Kazakhstan) differ significantly from those reported here. Whereas only northerly declinations have been identified in the Ordovician rocks from the Northern Tian Shan and Central Kazakhstan, results from coeval rocks from the Chingiz Range consistently show southerly declinations [Collins et al., 2003] (see also table 3). These differences in declination are compatible with a large-scale change in strike between the Chingiz range and the Northern Tian Shan and can be taken as evidence for oroclinal bending between the Chingiz and Northern Tian Shan [Collins et al., 2003]. Unfortunately, however, the data published by Collins et al., (2003) for the Chingiz Range show some substantial scatter making it difficult to draw firm conclusions.

Minimizing drift velocities and going back in time from accepted paleogeographic reconstructions for Permian times, shallow northerly paleolatitudes in the Silurian and Devonian and shallow southern paleolatitudes in the Ordovician seem rather reasonable and suggest that our assumption that the Ordovician magnetization has been acquired during periods of normal polarity of the Earth's magnetic field is justified (Fig. 1.5a).

All obtained data indicate that South Kazakhstan had good latitude agreement with Baltica from the Ordovician to the late Paleozoic, but was rotating slowly (Fig 1.5b).

1.5. Rotation of Kazakhstan relativele to Baltica and Siberia since Ordovician to Permian times

The post-folding component "A" for Silurian – Early Devonian rocks differs significantly from the expected reference directions for the Late Paleozoic, based on the Apparent Polar Wander Path for Siberia [Pechersky and Didenko, 1995] and Baltica [Smethurst et al., 1998]. This fact, indicating counterclockwise rotations within Kazakhstan with respect to both reference continents during the middle Devonian -Permian [Alexyutin et al., 2003], because an age of this magnetization has a range from middle Devonian to Carboniferous (Middle Devonian is a time of the folding and this magnetization has both polarities can not be Permian), but Permian rotations also are possible. However, a last case (Permian rotations) supposes a prefolding vector have being rotated too.

The comparison of the prefolding directions presented in this study with the APWPs for Baltica and Siberia indicate that from the Ordovician to Late Paleozoic Kazakhstan experienced a counterclockwise rotation relative to these two paleocontinents. An angle between our Ordovician declination and the reference Baltica declination about 80°, unlike the different our and the Sibiria reference declinations about 140° (Fig. 1.5a). However, we should note, that most of this rotation happened during middle Devonian-Permian time, as well post-folding direction from Silurian – early Devonian rocks (which has middle Devonian – Carboniferous age) rotated with respect Baltica reference direction to an angle about 90°. It means, that since Ordovician to middle Devonian South Kazakhstan had more or less the same orientation with respect Baltica.

a)

b)

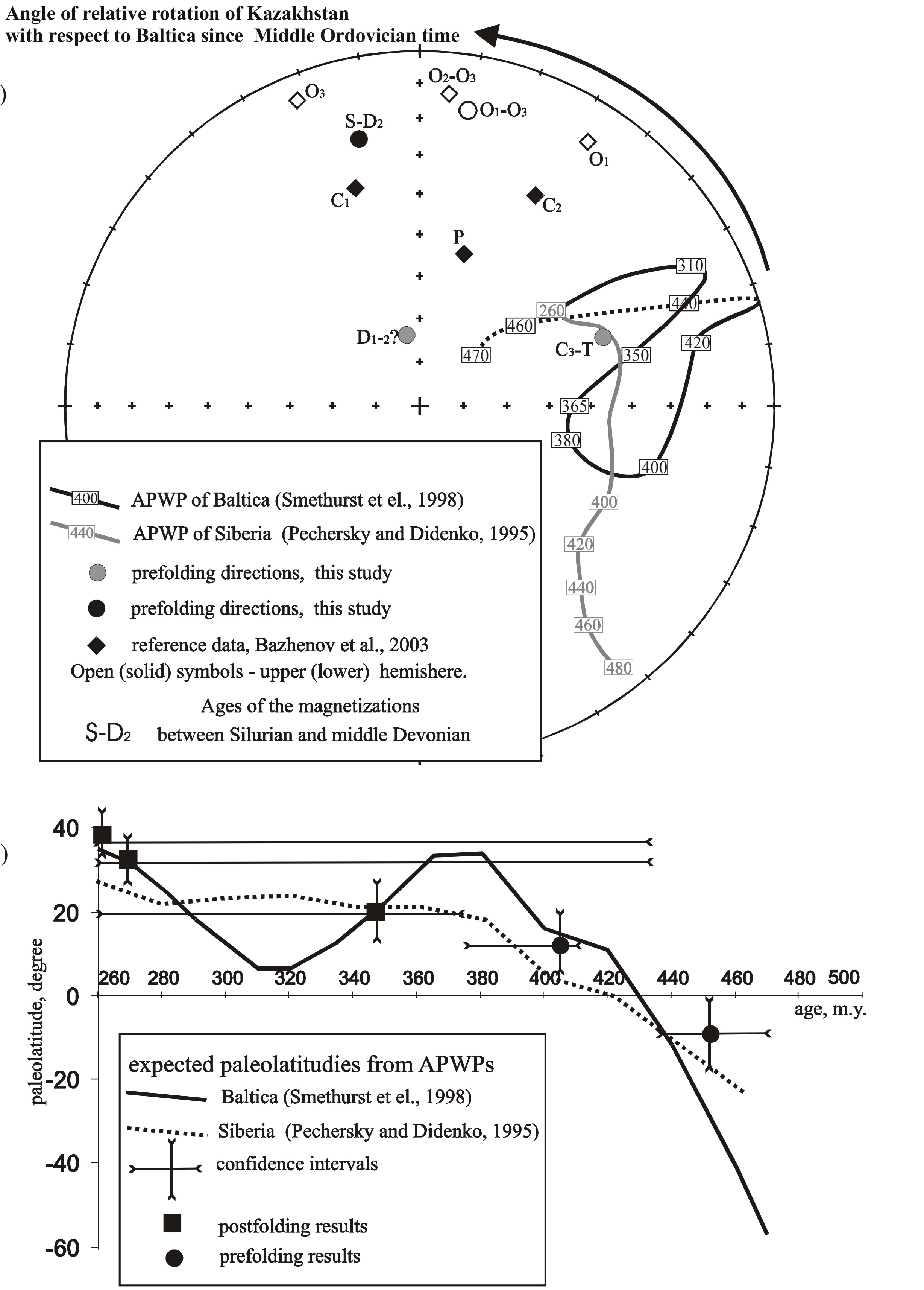


Figure 1.5. Observed and published paleomagnetic directions for the North Tian-Shan and Baltica, calculated for the locality 43N, 74.5E: a) comparison of directions, b) comparison of paleolatitudes.

1.6. Conclusions

1) Prefolding magnetizations were isolated: a) for the Lower Ordovician rocks in the Kendyktas ridge (D= 9.2°, I=-16.9°, k=26.9, α95=15.0°) and b) for Silurian and Lower Devonian rocks in the South Chu-Yili mountains (D= 346.9°, I=23.8°, k=20.8, α95=12.4°). This defines the paleolatitude of the Lower Paleozoic Stepnyak - North Tian Shan microcontinent as 8.6° ±8.7° (presumably southerly) for the Ordovician, and a paleolatitude of the Kazakhstan composite microcontinent as 12.4°±7.7° (presumably northerly) for the Early and Middle Devonian. A position in northern latitudes however cannot be excluded for the Ordovician time and resolving this uncertainty needs a more detailed study.

2) Postfolding magnetizations were isolated: a) for Lower Ordovician rocks (D=355.5°, I=35.6°, k=18.1, a95=9.6°), b) for Middle Ordovician rocks (D= 215.7°, I=-51.3°, k=55.4, a95=5.9°) and c) for Silurian and Lower Devonian rocks (D= 355.5°, I=35.6°, k=18.1, a95=9.6°). In case a) and b) the age of magnetization is post Late Ordovician. In the case c) it is post Middle Devonian in age.

3) For Ordovician to Late Paleozoic times the paleomagnetic data for Kazakhstan displays good latitude agreement with Baltica and experienced a counterclockwise rotation with respect to both Baltica and Siberia.

Part 2

Mid to Late Paleozoic paleomagnetism of Southern Kazakhstan

2.1. Tectonic setting

The Chu Yili mountain range runs northwest-southeast from lake Balkhash in the North to the Tian Shan mountains in the South (Fig. 2.1). The area is located within the southwestern segment of the Devonian volcanic belt of Kazakhstan, and borders by the Upper Paleozoic Chu-Sarysu basin in the Southwest and Balkhash Yili volcanic belt in the Northeast (Figs. 2.1 and 2.2).

The Lower Paleozoic tectonic units in the Chu-Yili region include several microcontinents, which were amalgamated during the Early and Late Ordovician [Apollonov, 2000; Avdeyev, 1990; Mikolaichuk et al., 1997; Nikitin and Nikitina, 2000]. During the Early and Middle Devonian, until the Givetian, the area was dominated by volcanism, which appears to have occurred in a continental active margin setting [Bakhteiev, 1987; Filippova et al., 2001; Kurchavov, 1994; Zonenshain et al., 1990b]. The mid Givetian is marked by active deformations, which are referred to as the Telbes orogenic event [Zaytsev, 1984]. During the late Givetian and Frasnian this shortening episode was followed by a sharp decrease of volcanic activity, by granite emplacement and by significant eastward shift of the volcanic belt. In the Famennian and Early Carboniferous the Chu-Yili and Chu-Sarysu areas form parts of a united epicontinental basin, dominated by shallow marine carbonate, siliciclastic, and non marine siliciclastic deposition [Abdulin (Ed.) et al., 1980; Nikitin et al., 1991]. In the Early Carboniferous (Serpukhovian) sedimentation ceased in the Chu-Yili area. This episode is coeval to the late Saur orogenic event, which is documented by an angular unconformity in the Balkhash-Yili volcanic belt and in many areas of eastern Kazakhstan [Zaytsev, 1984]. The Chu-Sarysu basin was active until the Late Permian and shallow marine conditions were prevailing here until the middle of the Bashkirian. Then the basin became isolated from the open sea and sedimentation continued in non-marine environments. In the Late Permian and Early Mesozoic, deformations affected marginal areas of the basin. Again, the timing of deformation is constrained by a regional unconformity of pre-Jurassic age [Zaytsev, 1984].

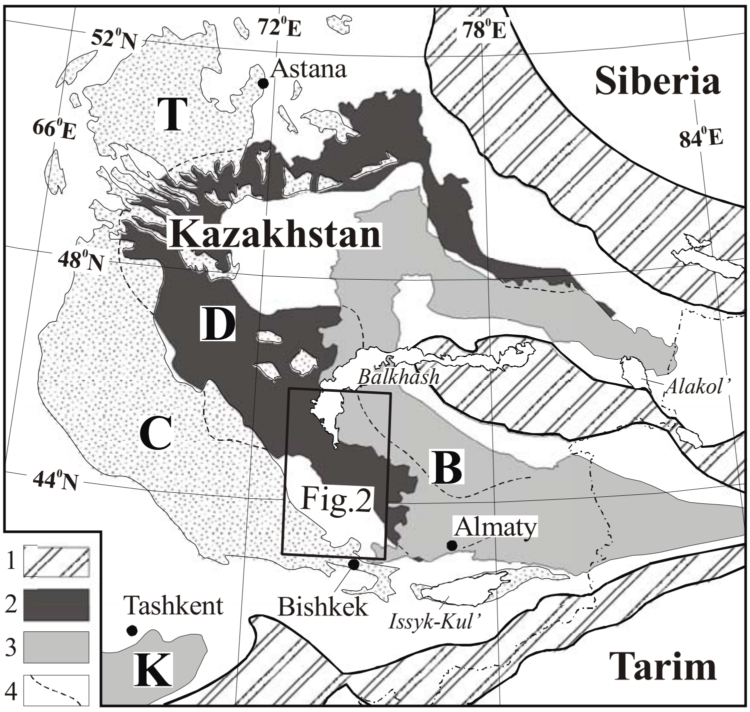


Figure 2.1. - Tectonic scheme of the Upper Paleozoic of Kazakhstan and adjacent areas. 1 - Upper Paleozoic thrust folded belts. 2 and 3- Volcanic belts: 2) - Lower and Middle Devonian, 3) - Carboniferous and Permian. D - Kazakhstan "Devonian" belt, B - Balkhash -Yili belt, K - Kurama belt. 3 - Carboniferous and Permian basins: T - Teniz basin, C - Chu-Sarysu basin. 4 - Boundary of the Devonian volcanic belt in subsurface. (Based on: Abdulin and Zaytsev, 1976; Bakhteiev, 1987)

2.2. Stratigraphy and deformation patterns

Devonian and Carboniferous rocks, which were the main target of this study, are widespread in the Chu-Yili mountains (Fig. 2.2). The Lower Devonian *Koktas formation* is dominated by basalts and andesitic-basalts with minor contributions of dacites, rhyolitic tuffs and lavas. Volcanic rocks alternate with and change laterally into red colored and green- to grey-colored sandstones, tuff-sandstones, tuff siltstones, conglomeratic sandstones and conglomerates. The Koktas formation is unconformably overlaying the Lower Paleozoic, and in turn is conformably overlain by the *Degherez formation* of the Lower and Middle Devonian. The latter one consists of red colored massive and cross-bedded sandstones and siltstones, with relatively few layers of tuff sandstones and acid tuffs. The red beds are laterally replaced by acidic lavas and tuffs, which are mapped as the *Karasai formation*. The section is topped by andesites, basalts, dacites, and subalcaline rocks which relate to Eifelian and Givetian stages of the Middle

Devonian. The age of the Lower and Middle Devonian formations is based on the occurrence of diagnostic flora and some isotope data [Abdulin et al., 1980; Nikitin et al., 1991].

Devonian rocks are deformed in large linear folds striking northwest-southeast. The age of the granitic batholites, cutting the fold structures is well constrained as late Givetian and early Frasnian based on stratigraphic data [Abdulin (Ed.), 1980; Myasnikov et al., 1979]. Following this line of argument the folding took place in the Givetian.

The Famennian and Carboniferous sequence unconformably overlays the Lower and Middle Devonian and Lower Paleozoic rocks. The section begins with red colored fluvial sandstones and conglomerates (up to several hundred meters thick), of the Dzhingildy formation (Famennian to Early Tournaisian). Up-section the facies change into shallow marine fossiliferous limestones, sandy limestones, green, gray and red-colored sandstones and siltstones, tuff sandstones and tuff siltstones, ranging in age from Tournaisian to Middle Visean. Further up the section consists mainly of non-marine deposits of the Late Visean and Serpukhovian ages [Abdulin et al., 1980; Myasnikov et al., 1979; Nikitin et al., 1991]. The Famennian and Carboniferous rocks are deformed as brachiform low angle folds. Time of folding within the major part of Chu-Yili mountains can be constrained as late Early Carboniferous, based on the emplacement age of the Middle Carboniferous sub-volcanic bodies [Abdulin (Ed.) et al., 1980; Myasnikov et al., 1979]. In the South, within the Kendyktas ridge, the deformations appears to be Late Permian or Early Mesozoic in age, as in analogy to the Chu-Sarysu basin, which this area directly borders on.

2.3. Paleomagnetic sampling

The paleomagnetic study in the Chu-Yili mountains has been carried out in ten areas (Fig. 2.2) and was concentrated on four stratigraphic levels: a) Lower Devonian; b) Lower and Middle Devonian; c) Upper Devonian and Lower Carboniferous; and d) Lower Carboniferous.

a) Andesitic basalts, basalts and red-colored sandstones, of the Lower Devonian Koktas formation were sampled in the stratotype area within the Koktas syncline, locality KOK (Fig.2 area 3), and in the Anderkenyn – Akchoku ravine locality AND (Fig. 2.2 area 7). b) Red beds of the Lower and Middle Devonian Degherez formation were studied in three areas North and East of Khantau, locality KHA (Fig. 2.2 areas 4, 5, and 6). c) Upper Devonian and Lower Carboniferous red beds of the Dzhingildy formation were collected in Kendyktas ridge Southwest of Otar, localities OTA and ODA (Fig. 2.2 areas 9 and 10 respectively), and Northwest of Espe, locality ESP (Fig. 2.2 area 8). d) Lower Carboniferous (Lower Visean) rocks were studied on the western shore of the lake Bakhash near the villages Kashkanteniz - locality SAR, and Mynaral – locality MIN (Fig. 2.2 areas 1 and 2 respectively).

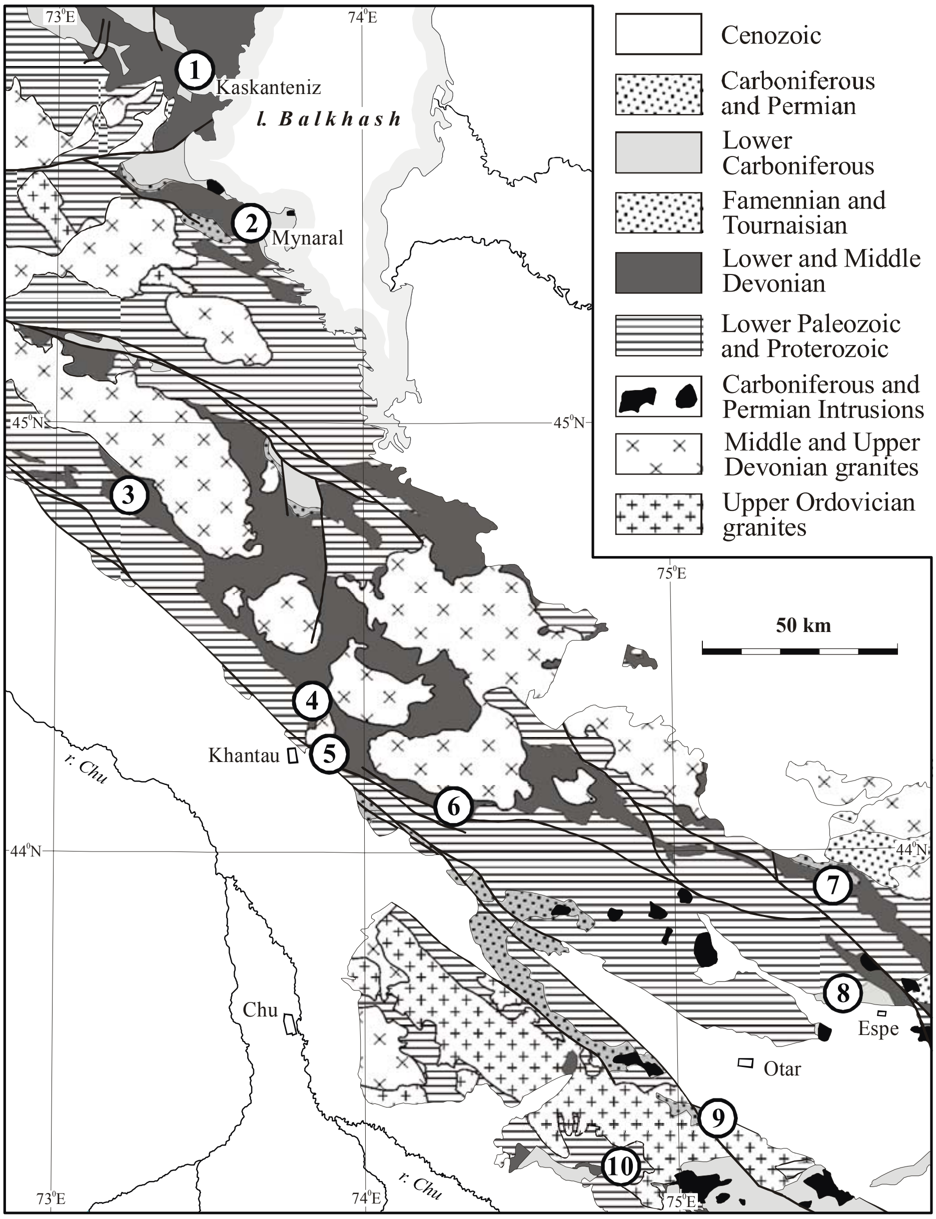


Figure 2.2. - Schematic geological map of the Chu-Yili and Kendyktas mountains. Numbers show sampling areas: 1- South of Saryshagan (SAR); 2 - Mynaral (MIN); 3 - Koktas syncline (KOK); 4 -6 Khantau area (KHA): 4- sites KHA 1-8; 5- sites KHA 9-11; 6- sites KHA 13-16; 7- Anderkenyn - Akchoku ravine (AND); 8 - Espe (ESP); 9 and 10 - Southwest of Otar: OTA and ODA respectively.

2.4. Results

Two components of magnetization were defined in the Lower Devonian basalts and red beds of the Koktas formation (localities ADN and KOK, Fig. 2.2 areas 3 and 7). *Component A* was isolated in the temperature interval of 300° - 540°, pointing towards magnetite as the carrier of magnetization (Fig. 2.3a,b). Unfortunately, however in spite of the fact that many samples show stable demagnetization behavior, the within site scatter of the directions is large. These sites will not be discussed any further. The dual polarity component A has an in situ direction of D= 010.4°, I=+54.8°, k=7.2, α95=26.8. Component A fails the fold test, and must, therefore, postdate the middle Givetian deformation event (Table 2.1, Fig. 2.4a). *Component B* passes the fold test and is prefolding in age. Component B was isolated between 520 – 650°C in basaltic rocks and 620 - 670°C in red sandstones (Figs. 2.3a and 2.3b). This suggests that magnetization B is carried by both magnetite in basalts and by hematite in sandstones. Since in several sites component B was isolated only in one or two samples, the mean direction for B was calculated both on site level and on sample level. However, no significant differences in the mean directions were observed (site mean direction: D= 357.3°, I=+75.8°, k=16.5, α95=14.1°; sample mean direction: D=348.5°, I=73.6°, k=12.6, α95=7.0°, see also Table 1 and figures 4a,b,c). In addition, dual polarities were observed in some sites, although we note some differences between normal and reversed magnetizations. Based on rock age and time of folding component B can be dated as late Early Devonian or early Middle Devonian in age.

Only the post folding overprint component A was identified in the red beds of the Lower to Middle Devonian Degherez formation. This component with an in situ direction of D=033.1°, I=+66.6°, k=18.5, α95=11.5° (Table 2.1, Fig. 2.4d) was isolated in the temperature interval 300 - 630° (Fig. 2.3c), indicating that the magnetization is carried by both magnetite and hematite. Again as in the samples from the Koktas Formation normal and reverse polarities were identified. Based on the time of folding the age of component B must be post mid Givetian.

The red beds of the Famennian and Lower Tournasian Dzhingildy formation demonstrate significantly different paleomagnetic patterns in the South of Chu-Yili mountains (locality ESP; Fig. 2.2 area 8) and in the Kendyktas ridge (localities OTA and ODA, Fig. 2.2 areas 9 and 10).

At the locality ESP only one component A with in situ direction D = 190.4, I=-38.6, k=71.8, α95=7.2 (Table 2.1, Fig. 2.4e) carried by magnetite was isolated in the temperature interval 300 - 570° (Figs. 2.3d,e). The fold test for component A is negative and, based on the Early Carboniferous age of folding, the time of magnetization can be unambiguously constrained as being Late Early Carboniferous in age or younger.

In the Kendyktas ridge two components of magnetization were isolated (Figs. 2.3f,g): component A (D=069.5°, I=+43.7°, k=26.7, α95=9.5°) carried by magnetite, and component B (D=060.9°, I=+36.9°, k=12.7, α95=19.6°) carried by hematite (Figs. 2.4f,g). Both A and B components pass the fold test and are interpreted to be prefolding in age. The timing of folding in this area is not well constrained, but most probably took place during Late Permian to Early Mesozoic (see above), and the time of magnetization is, therefore, based on comparison with the APWP for Baltica thought to be Late Paleozoic.

Only one component carried both by magnetite and hematite was isolated in the temperature interval 300-630°C (Fig. 2.3i) in Lower Visean red sandstones and siltstones at localities SAR and MIN (Fig. 2.2, areas 1 and 2). This component has an in situ direction of D=197.0°, I=-63.4°, k=51.1, a95=10.8° (Table 2.1, Fig. 2.4i) and fails the fold test. All but two samples are of inverse polarity.

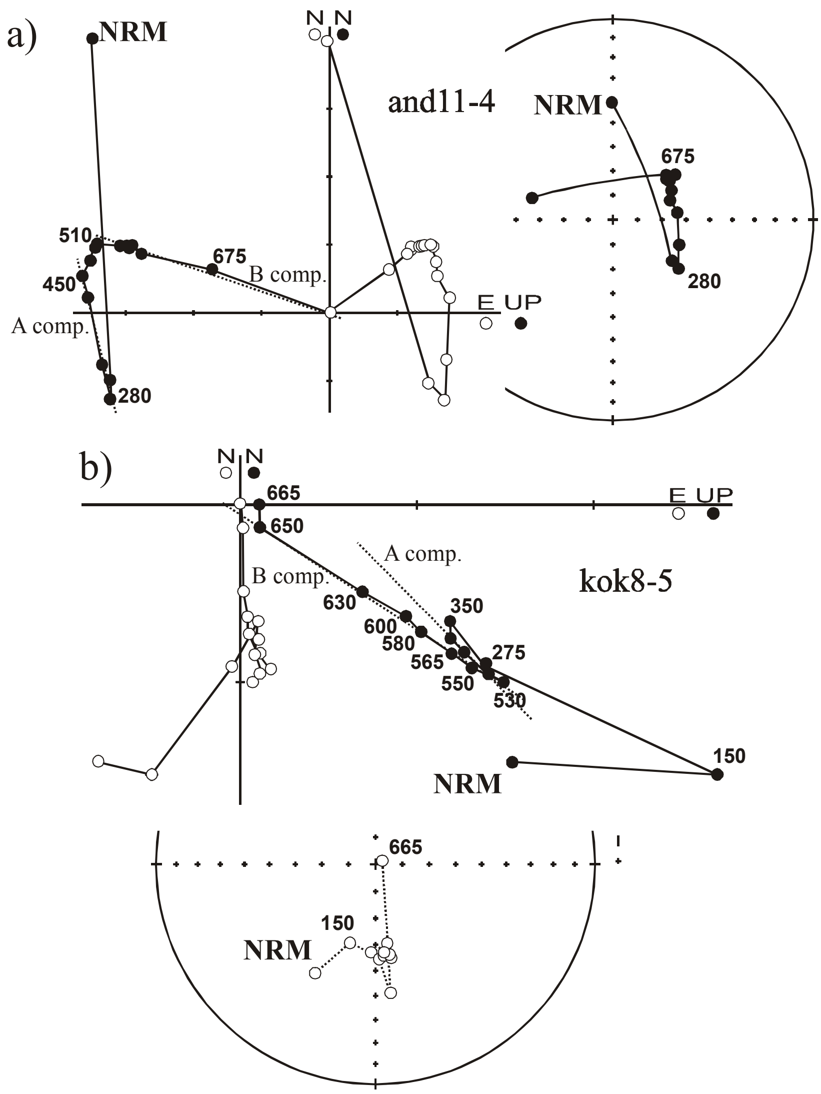


Figure. 2.3. Orthogonal plots of thermal demagnetization data. Temperatures are in °C. Stratigrafic system.

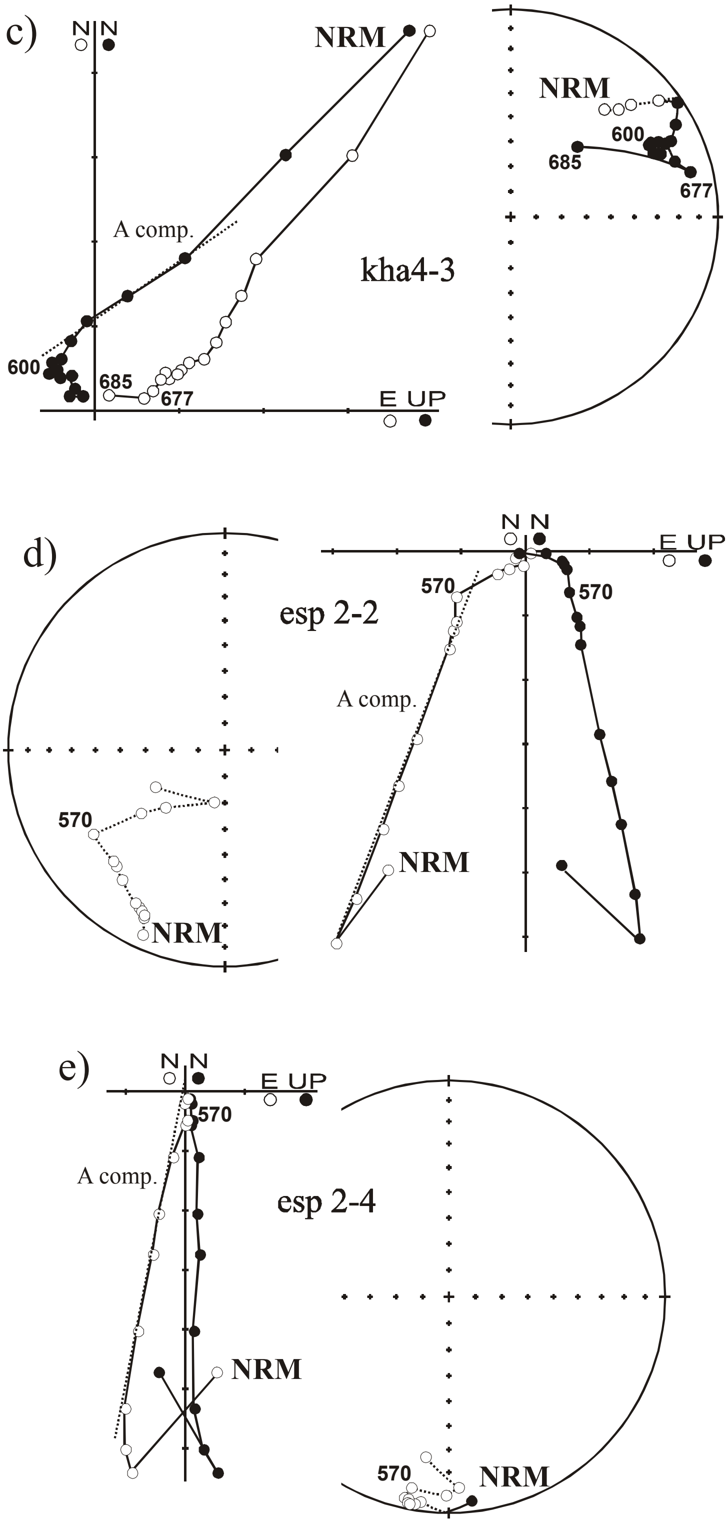


Figure. 2.3. CTD.: Orthogonal plots of thermal demagnetization data.

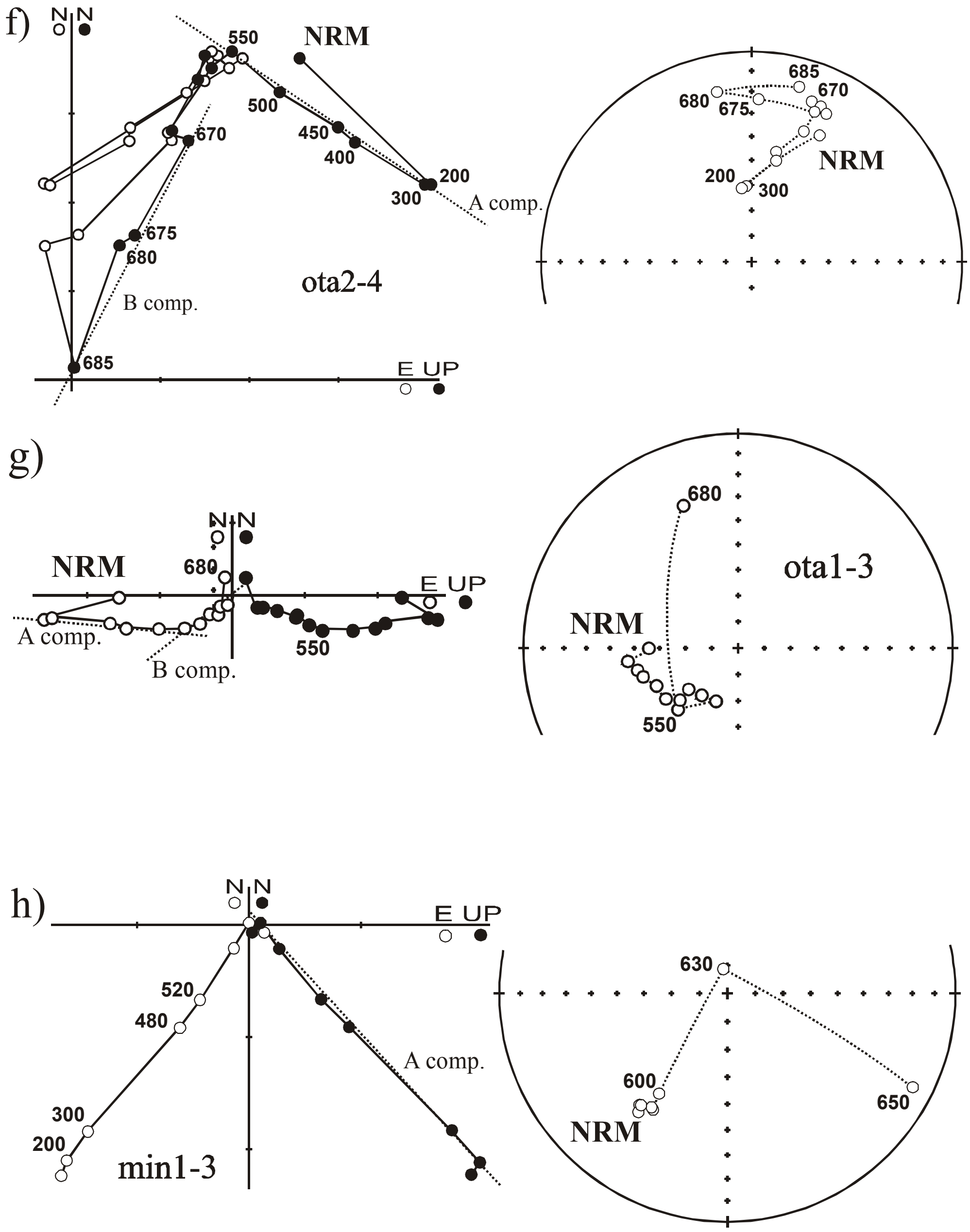


Figure. 2.3. CTD.: Orthogonal plots of thermal demagnetization data.

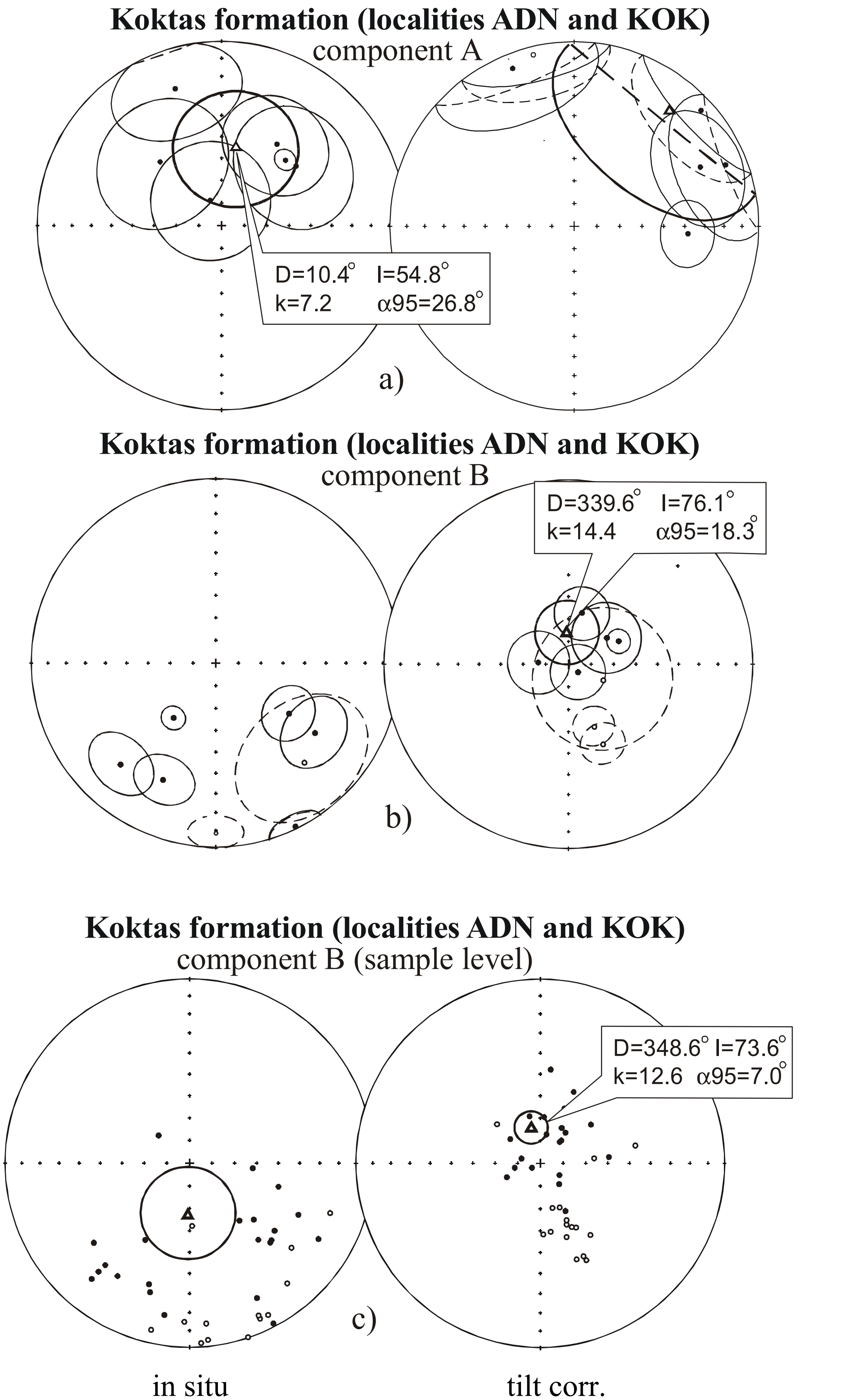


Figure 2.4. Site-mean derections and α95 confidence circles. Open (solid) symbols - upper (lower) hemishere. The mean directions are listed in Table 2.1.

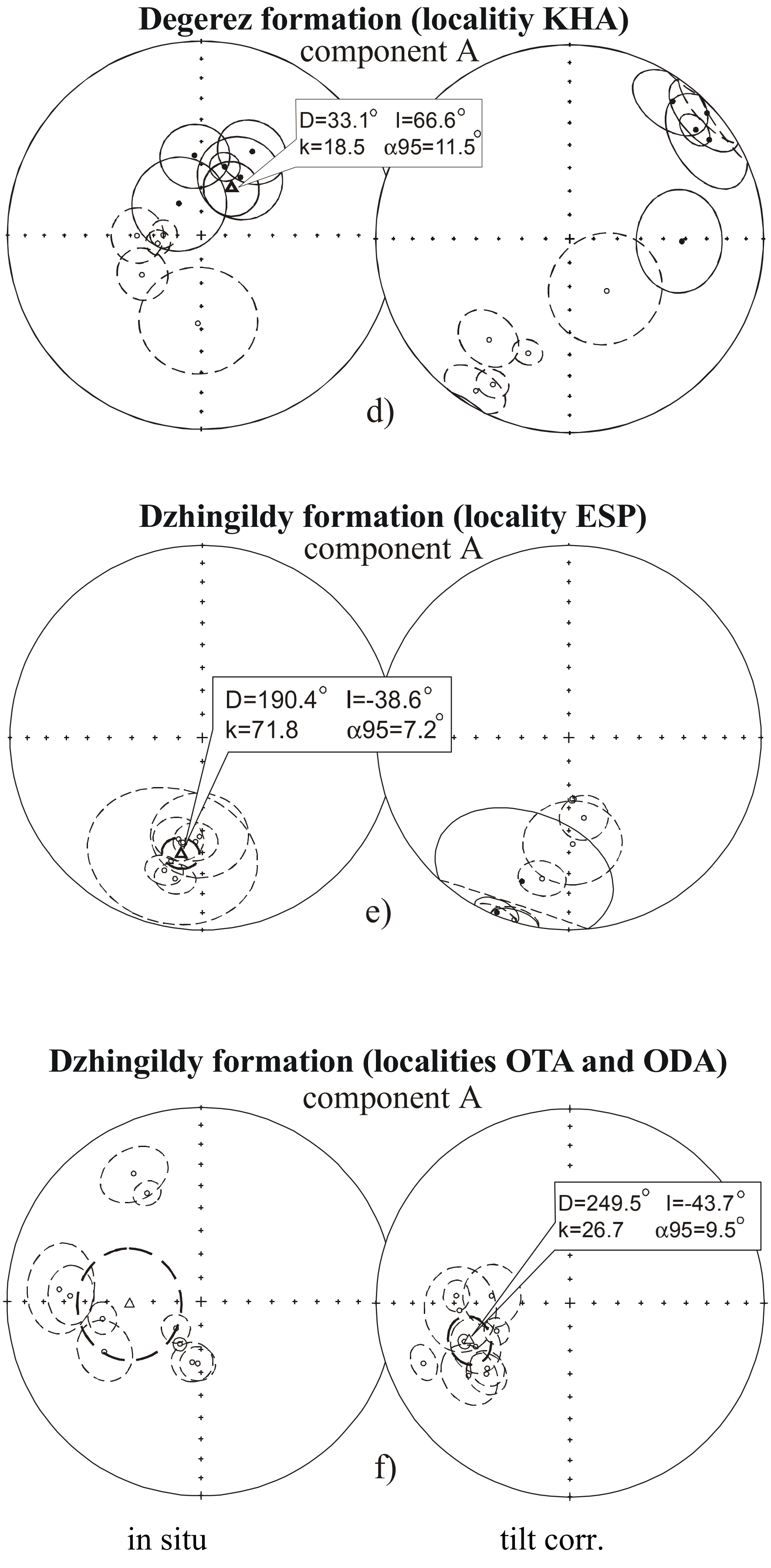


Figure 2.4. CTD.: Site-mean derections and α95 confidence circles.

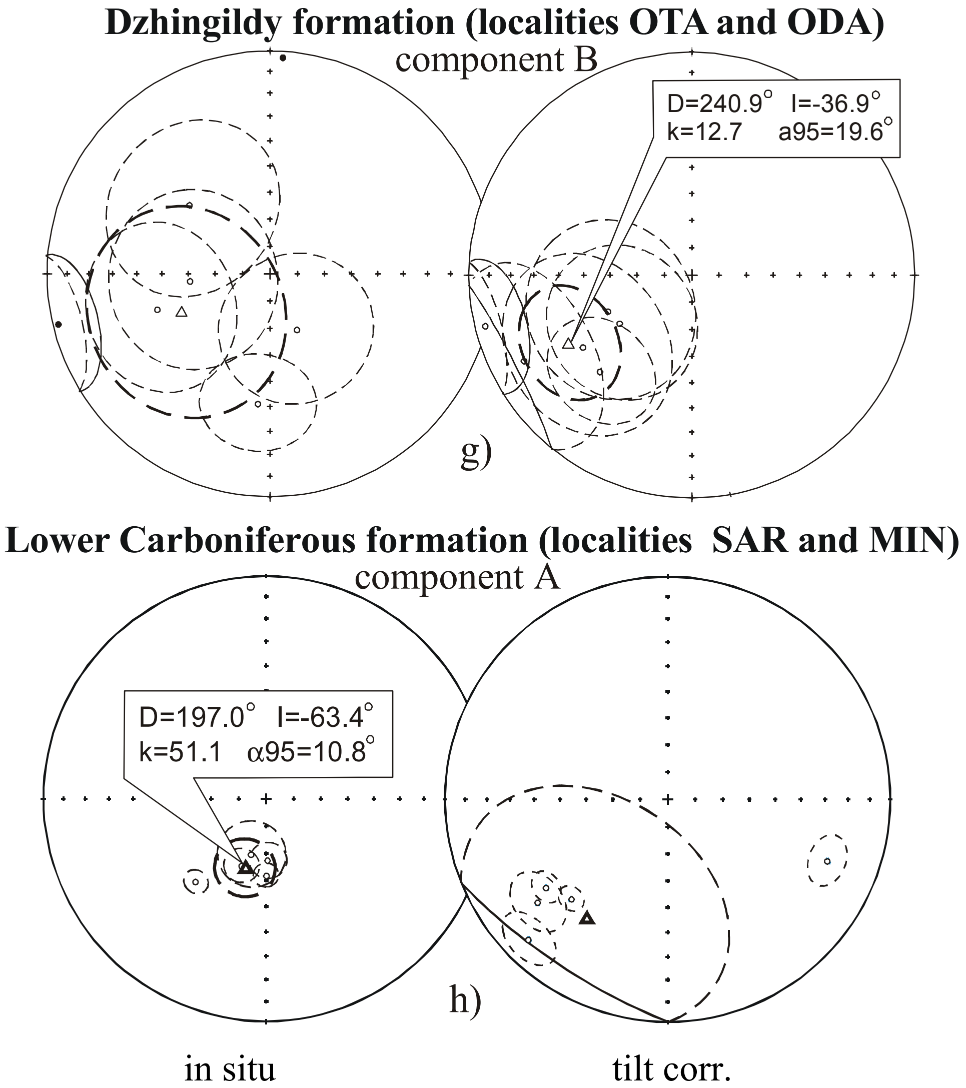


Figure 2.4. CTD.: Site-mean directions and α95 confidence circles.

Table 2.1. Site – mean directions.

Site	Number of spec/	In situ				Tilt.corr.			
		D	I	k	α_{95}	D	I	k	α_{95}
Lower Carboniferous (Lower Visean) rocks (MIN and SAR localities)									
Component A									
SAR6	5	178.1	-67.4	131.3	6.7	231.6	-26.5	55.3	10.4
SAR7	6	200.1	-63.9	112.1	6.4	234.2	-33.2	149.2	5.5
SAR8	5	180.0	-62.0	285.3	4.5	224.8	-12.5	69.7	9.2
SAR9	4	194.6	-69.0	56.8	12.3	110.9	-24.1	131.1	8.1
MIN1	4	220.2	-49.7	434.5	4.4	224.2	-37.9	395.6	4.6
Mean		**197.0**	**-63.4**	**51.1**	**10.8**	**213.9**	**-35.2**	**3.6**	**47.4**
Upper Devonian and Lower Carboniferous									
ESP locality									
Component A									
ESP1	6	181.6	-47.2	13.0	19.3	178.0	-43.7	13.0	19.3
ESP2	5	190.9	-26.1	105.2	7.5	196.5	-0.6	105.2	7.5
ESP3	5	196.0	-28.6	118.2	7.1	202.5	2.0	118.2	7.1

Table 2.1. **CTD.**

ESP4	5	190.5	-43.8	>999.9	1.6	177.0	-63.7	>999.9	1.6
ESP5	6	180.2	-29.7	219.6	5.2	169.9	-47.9	219.6	5.2
ESP6	6	193.2	-44.8	46.8	9.9	169.4	-54.9	46.8	9.9
ESP7	5	194.2	-34.1	6.5	32.5	198.3	22.6	6.5	32.5
Mean		**190.4**	**-38.6**	**71.8**	**7.2**	**190.2**	**-24.1**	**5.9**	**27.2**
OTA and ODA localities									
Component A									
ODA8	4	242.1	-43.9	58.6	12.1	234.5	-35.9	58.6	12.1
ODA9	6	259.8	-48.0	109.6	6.4	247.8	-19.6	109.6	6.4
ODA10	3	275.1	-28.5	57.4	16.4	266.5	-42.1	57.4	16.4
ODA11	6	272.5	-33.9	37.8	11.0	245.7	-45.3	37.8	11.0
OTA1	5	222.7	-74.5	161.1	6.0	273.5	-40.9	161.1	6.0
OTA2	5	188.3	-64.1	81.6	8.5	229.6	-42.8	81.6	8.5
OTA3	6	183.0	-63.7	84.1	7.3	231.6	-44.6	84.1	7.3
OTA4	5	206.4	-70.0	759.8	2.8	249.8	-41.5	759.8	2.8
OTA6	6	332.2	-26.5	28.9	12.7	275.0	-56.6	28.9	12.7
OTA7	5	333.5	-37.7	197.0	5.5	248.8	-56.6	197.0	5.5
Mean		**267.0**	**-59.9**	**5.5**	**22.7**	**249.5**	**-43.7**	**26.7**	**9.5**
Component B									
	6	203.8	31.0	31.1	12.2	129.4	84.6	31.1	12.2
ODA8	3	265.3	-61.4	15.7	32.2	247.0	-56.5	15.7	32.2
ODA9	6	252.3	-46.9	6.1	29.5	243.1	-17.0	6.1	29.5
ODA11	4	256.3	3.6	25.2	18.7	255.7	-5.7	25.2	18.7
OTA1	5	185.3	-40.7	16.3	19.5	223.2	-39.7	16.3	19.5
OTA4	3	154.6	-67.0	20.3	28.1	235.6	-57.9	20.3	28.1
OTA6	4	310.3	-50.9	9.1	32.2	236.1	-40.8	9.1	32.2
Mean		**244.5**	**-54.8**	**4.1**	**38.0**	**240.9**	**-36.9**	**12.7**	**19.6**
Lower and Middle Devonian Degherez formation (KHA and SAR localities)									
Component A									
KHA1	4	31.3	48.2	44.7	13.9	47.5	4.6	44.7	13.9
KHA3	5	355.3	56.2	30.7	14.0	36.7	12.6	30.7	14.0
KHA4	4	18.9	59.4	222.3	6.2	49.1	15.1	222.3	6.2
KHA5	3	34.1	60.6	49.9	17.6	54.6	12.6	49.9	17.6
KHA11	6	324.5	73.8	12.4	19.8	91.2	41.8	12.4	19.8
KHA13	6	269.8	-62.9	36.1	11.3	218.8	-34.0	30.9	12.2
KHA14	5	272.0	-74.1	173.5	5.8	200.3	-37.8	173.5	5.8
KHA15	6	236.6	-60.1	39.4	10.8	211.5	-8.8	39.4	10.8
KHA16	6	260.5	-71.6	166.3	5.2	208.2	-16.8	166.3	5.2
SAR3	3	182.1	-52.9	28.1	23.7	143.8	-63.4	28.1	23.7
Mean		**33.1**	**66.6**	**18.5**	**11.5**	**40.0**	**26.5**	**7.8**	**18.4**
Lower Devonian Koktas formation (KOK and AND localities)									
Component A									
KOK1	6	336.0	77.8	7.3	26.5	68.0	12.7	7.3	26.5
AND5	6	341.3	22.6	8.2	24.8	346.7	-4.6	8.2	24.8
AND6	5	51.1	47.3	9.1	26.9	47.6	7.8	9.1	26.9
KOK3	4	34.0	45.6	17.2	22.8	65.0	25.5	17.2	22.8
KOK4	5	44.0	48.9	267.6	4.7	94.0	38.1	34.3	13.3
AND4	4	316.3	50.4	10.9	29.1	338.7	9.4	10.9	29.1
Mean		**10.4**	**54.8**	**7.2**	**26.8**	**39.1**	**19.5**	**3.2**	**44.3**
Component B									
KOK4	5	138.0	-29.0	8.2	28.4	114.0	-73.3	6.8	31.6
KOK5	6	154.0	0.4	56.6	9.0	158.0	-60.3	56.4	9.0
KOK8	5	180.0	-9.1	68.6	9.3	157.0	-51.4	67.2	9.4
ADN1	6	203.8	31.0	31.1	12.2	129.4	84.6	31.1	12.2
AND2	3	223.1	25.4	80.8	13.8	273.3	76.8	80.8	13.8
AND7	3	217.6	59.1	541.9	5.3	65.4	65.5	541.9	5.3

Table 2.1. **CTD.**

AND11	4	125.1	34.7	38.0	15.1	54.8	69.6	36.1	15.5
AND12	6	124.5	50.2	32.1	12.0	14.3	66.8	32.1	12.0
Mean (Site level Fig.4b)		**262.4**	**73.6**	**1.7**	**63.4**	**357.3**	**75.8**	**16.5**	**14.1**
Mean (Sample level Fig.4c)		**307.9**	**72.8**	**1.7**	**28.0**	**348.5**	**73.6**	**12.6**	**7.0**

D - declination; I - inclination; k - precision parameter (Fisher, 1953); α_{95} - radius of confidence circle.

2.5. Interpretation of prefolding directions – paleogeographic implications

The most striking result obtained in this study is probably the direction of the pre-folding component of magnetization identified in rocks of early Devonian age from the Koktas formation (localities ADN and KOK, Fig. 2.2 areas 3 and 7), which is significantly different from both the reference directions for Baltica and Siberia. The resulting paleolatitude of 64° exceeds any expected value for the Paleozoic (Table 2.2).

Among possible explanations of these steep inclinations, which are in contrast to the shallow inclinations observed in most of the Paleozoic results in the area the following alternatives:

a) Fast motion of Kazakhstan towards the North in the Early and Middle Devonian followed by a swing back into lower latitudes in the Late Devonian. It should be pointed out that similar trends of motion can be recognized in the APWPs of Baltica [Smethurst et al., 1998] (Fig. 2.5).

b) Since the results for the Ordovician and Silurian are based on sedimentary rocks inclination swallowing cannot be ruled out. Similar observations have been documented elsewhere in the Tian Shan in red beds and volcanic rocks of Tertiary age [Bazhenov and Mikolaichuk, 2002].

Table. 2.2. Virtual geomagnetic pole positions (all directions are recalculated to normal polarities).

Locality	Age the rocks	Loc. Lat. [°N]	Loc. Long. [°E]	D [°]	I [°]	A95 [°]	Pol. Lat [°]	Pol. Long [°]	dn/dp [°]	φ [°]	Age of folding	Age of magnetization
MIN and **SAR**	**Lower Visean**	**45°59'**	**73°34'**	**17.0**	**63.4**	**10.8**	**78.1**	**162.4**	**13.5/17.1**	**45.0 +20.5/-11,8**	**Post early Visean**	**Post Early Carboniferous**
ESP	**Upper Devonian - Lower Carboniferous**	**43°22'**	**75°08'**	**10.4**	**38.6**	**7.2**	**66.7**	**230.0**	**5.1/8.6**	**21.8 +5.4/-4.8**	**C1 (Middle Visean or Middle Serpukhovian ?)**	**Post Early Carboniferous**
OTA and **ODA**	**Upper Devonian and Lower Carboniferous**	**43°15'**	**74°50'**	**69.5**	**43.7**	**9.5**	**31.7**	**158.2**	**7.4/11.9**	**25.5 +8.3/-6.7**	**Late Permian or Early Mesozoic (?)**	**Early Carboniferous - Triassic**
KHA and **SAR**	**Lower and Middle Devonian**	**44°21'**	**73°51'**	**33.1**	**66.6**	**11.5**	**67.0**	**139.9**	**15.6/18.9**	**49.1 +18/-13.5**	**D2, Givetian (?)**	**Post Middle Devonian**
KOK and **AND**	**Lower Devonian** (postfolding component)	**43°54'**	**75°32'**	**10.4**	**54.8**	**26.8**	**78.3**	**209**	**26.8/37.9**	**35.3 +38.2/-20.4**	**D2, Givetian** for folds **and Late Paleozoic (?) to early Mesozoic** for bends	**Post Middle Devonian**
KOK and **AND**	**Lower Devonian** (prefolding component)	**------**	**------**	**348.5**	**73.6**	**7.0**	**72.9**	**55.4**	**11.3/12.6**	**59.5 +12.2/-10.4**	**------**	**Early - Middle Devonian**

Loc. Lat. and Loc. Long – the locality position; D - declination; I - inclination; k - precision parameter (Fisher, 1953); A95 - radius of confidence circle. Pol. Lat, Pol. Long and dp/dn are the latitude, longitude, and radius of 95% confidence circle of the paleopole, respectively; φ - paleolatitude.

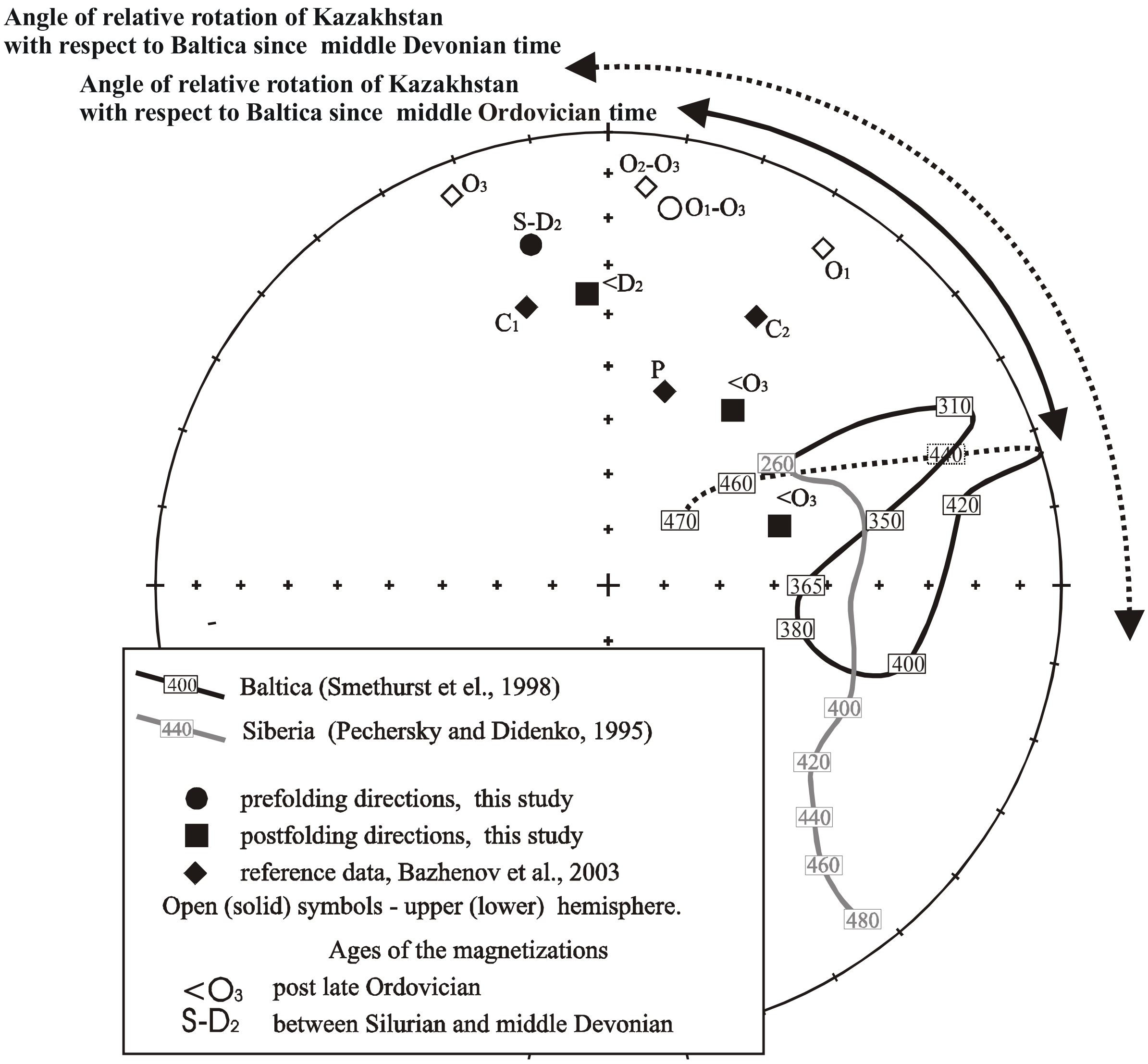


Figure 2.6. Observed (this study) and reference directions for the North Tian-Shan and Baltica.

2.6. Rotation relative to Baltica and Siberia since Middle Devonian to Permian times

Pre-folding components of magnetization have been identified in Ordovician, Silurian, Devonian and Carboniferous rocks of Southern Kazakhstan and in the Northern Tian Shan [Alexyutin et al., in press; Bazhenov et al., 2003] and show declinations which are significantly different to the relevant reference directions derived from both the APWPs for Baltica [Smethurst et al., 1998] and Siberia [Pechersky and Didenko, 1995]. These differences indicate counterclockwise rotations of Southern Kazakhstan with respect to these two cratons of up to 80° (w.r. to Baltica) and 140° (w.r. to Siberia) since the Ordovician. Most of this rotation took place between Mid Devonian and Permian times (Fig. 2.6).

2.7. Conclusions

1. The Prefolding component of D=348.5°, I=73.6°, k=12.6, α95=7.0° isolated for the Lower Devonian basalts (Koktas formation) implies a paleolatitude of 59.5° ± 12.2° N.

2. The Prefolding direction of D=69.5°, I=43.7°, k=26.7, α95=9.5°, isolated in the Upper Devonian – and Lower Carboniferous red beds implies a paleolatitude of 21.8° ± 5.9° N.

3. Overprint components from South Kazakhstan are characterized by antiparallel polarities and different directions and were acquired during several episodes of remagnetization during Devonian to Permian times.

Part 3

Mid to Late Paleozoic Paleomagnetism of Central North Kazakhstan and the Chingiz Ridge

3.1. Tectonic setting

As it was noted in chapter 1, the Devonian volcanic belt of Kazakhstan consists of three main segments: the Southwestern, the Central and the Northeastern branch.

North Kazakhastan has a very complicated lower Paleozoic structure and includes a series of rigid blocks, separated by ophiolite zones. The rigid blocks have different ages and are represented by fragments of paleovolcanic arcs and Precambrian (or of unknown age) massives with a sialic (or unknown) basement [Yakubchuk, 1990]. The Eastern part of the Northern Kazakhstan segment is known as the Chingiz Ridge, which runs from the area north of the city of Pavlodar to Lake Alacol.

All sutures in North Kazakhstan were closed before the Ordovician, and since then North Kazakhstan acted as a single block with an active plate boundary on its southern margin (in present day coordinates). In the Lower Silurian – Lower Devonian shallow marine and non-marine sediments were deposited in depressions in the internal parts of North Kazakhstan. Since the Lower Devonian the volcanic belt formed as a result of subduction under the southern margin of North Kazakhstan.

The Central Kazakhstan segment is the northward continuation of the South Kazakhstan segment and is dominated more or less by similar tectonic structures. It consists of several rigid blocks, which have been amalgamated during (or before) Ordovician times (see chapter 1). Presently, big depressions, filled by Late Carboniferous – Permian sediments, dominate the tectonic pattern of Central Kazakhstan. Several tectonic blocks, built up by Lower to Mid Paleozoic rocks can be identified on the peripheral parts of these late Paleozoic depressions.

Figure 3.1. Tectonic setting of Paleozoic Kazakhstan. 1 - Upper Paleozoic thrust and fold belts; 2- Subduction related volcanic belts: a) Lower and Middle Devonian, and b) Carboniferous and Permian deposits. ED, TO, NS – sampled localities.

3.2. Geology and sampling

A paleomagnetic study has been carried out in two areas in North Kazakhstan and in one area in Central Kazakhstan.

In North Kazakhstan, Silurian redbeds were sampled to the north of the city of Karaganda (near pump station-10, locality NS, Fig. 3.1) and to the southeast of the village of Dogolan (locality TO, Fig.3.1).

To the north of Karaganda (locality NS) Silurian sediments, consisting of polymictic and volcanomictic sandstones, conglomerates, gravelites and tuffs (total thickness about 2800 m) [Bekzhanov et al., 2000] are well exposed. The age of these rocks can only be derived from their tectonic position and must be older then Lower Devonian, but younger then Late Ordovician. Several folding events are known in the area, with major folding during the Late Ordovician, and only mild deformation in the Middle Devonian.

In the Chingiz range, Lower Silurian redbeds were sampled near the village of Dologan (localities TO and BUR). Here, redbeds of the Alpeisskaya suite unconformably overlie Upper Ordovician sediments and are in turn unconformably overlain by Lower Devonian redbeds. Abundant graptolite fauna confirm the Lower Silurian age of the Alpeisskaya suit, which is the

Silurian stratotype in Chingiz Ridge. The age of folding in the area is unclear and the latest fold event may be even Mesozoic in age.

In Central Kazakhstan, Lower - Upper Devonian redbeds (sand- and siltstones) were sampled near the village of Egendy (locality ED), along the banks of river Kara-Kengir. The age of these rocks is based on brachiopod fauna. An Early Carboniferous folding event is manifested by gently folded Visean – Serpukhovian rocks of the Dalnenskay suite. Note, that here the age of folding is not completely clear, as Permian and even Jurassic rocks to the North and East from the sampled locality are also gently deformed.

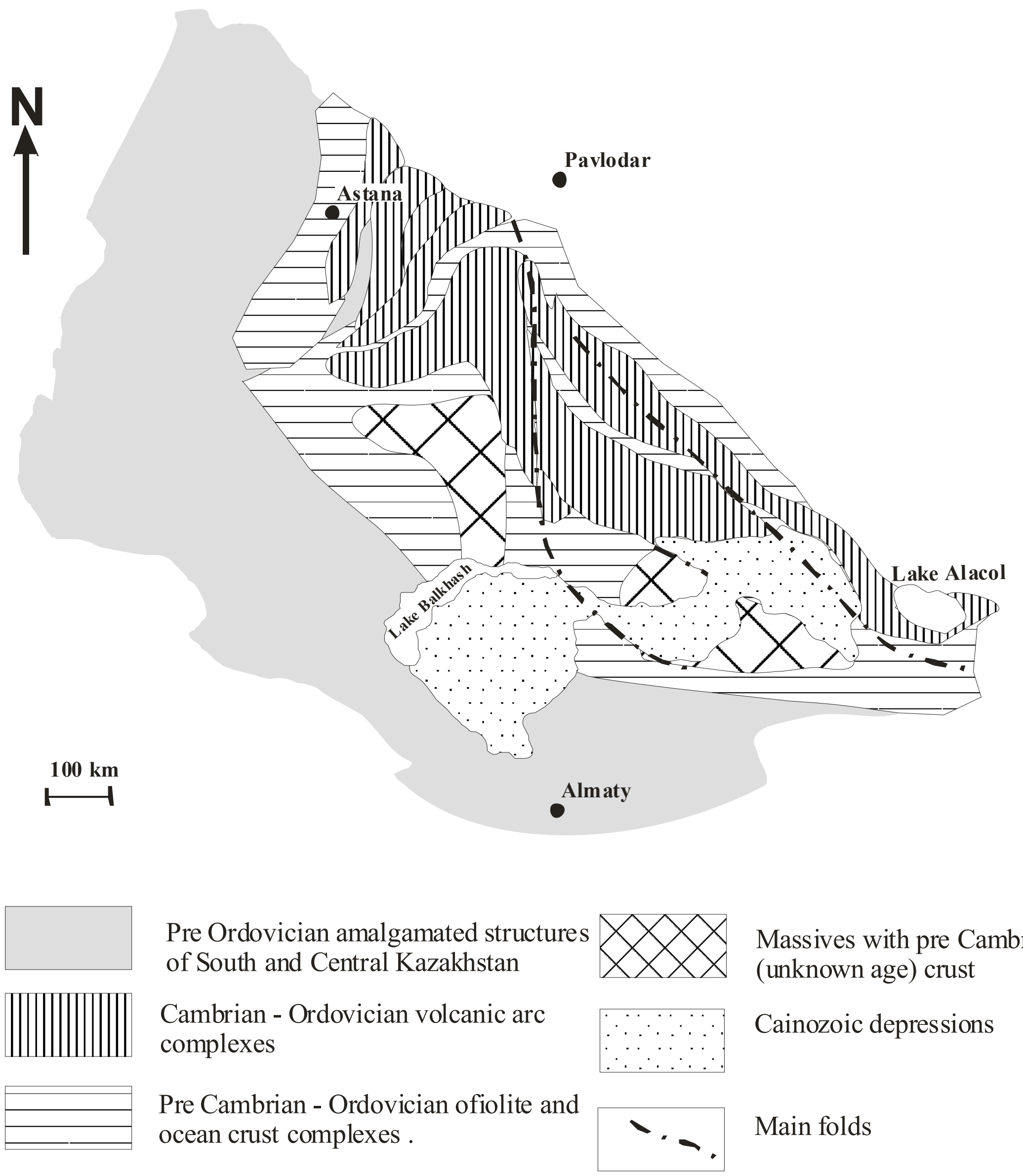


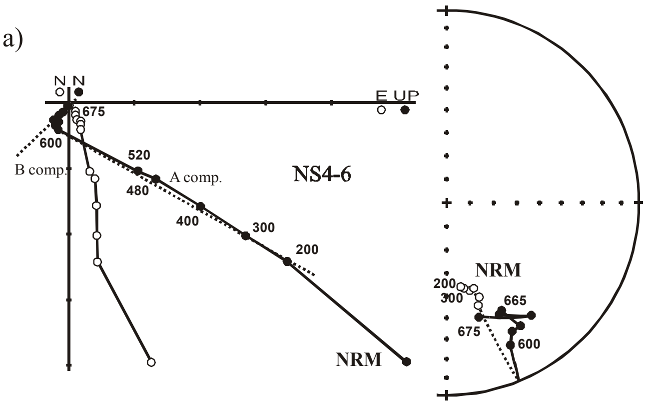
Figure 3.2. Tectonic pattern of North Kazakhstan (simplified after [Yakubchuk, 1990]).

3.3. Results

All redbed samples from North and Central Kazakhstan yield two remanence components. Component A was isolated in temperature interval of 200°-560°C (Fig. 3.3 a,b,c,d,i,f,g) and is carried by magnetite. Component B (Fig. 3.3 a,b,c,d,i,f,g), carried by hematite, has been isolated in the temperature interval of 600°-660°C.

In Silurian-Lower Devonian redbeds, sampled to the North of Karaganda near pumpstation-10 (locality NS) both components A and B display a big scatter within sites (Fig. 3.4). For this reason the average mean has been calculated on the sample and site levels (Figs. 3.5 and 3.6, table 3.1-3.2). Both components A and B fail the fold test and are therefore interpreted to be post Late Devonian in age. However, directions of both polarities have been identified in both A and B components. The rather steep inclinations of these components do not agree with any reference direction, calculated from the APWPs for Siberia and Baltica.

a)



b)

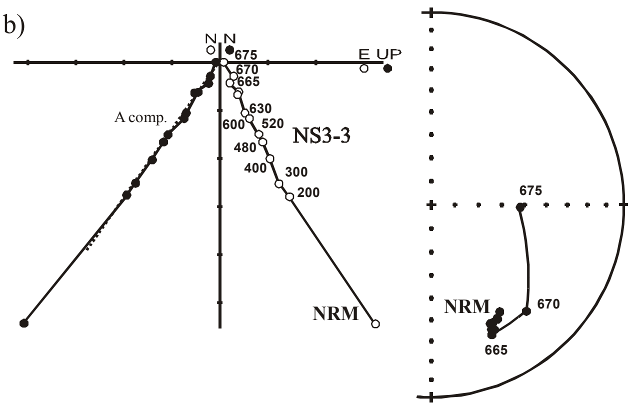


Figure 3.3. Orthogonal plots of thermal demagnetization data. Temperatures are in °C. Stratigraphic coordinates.

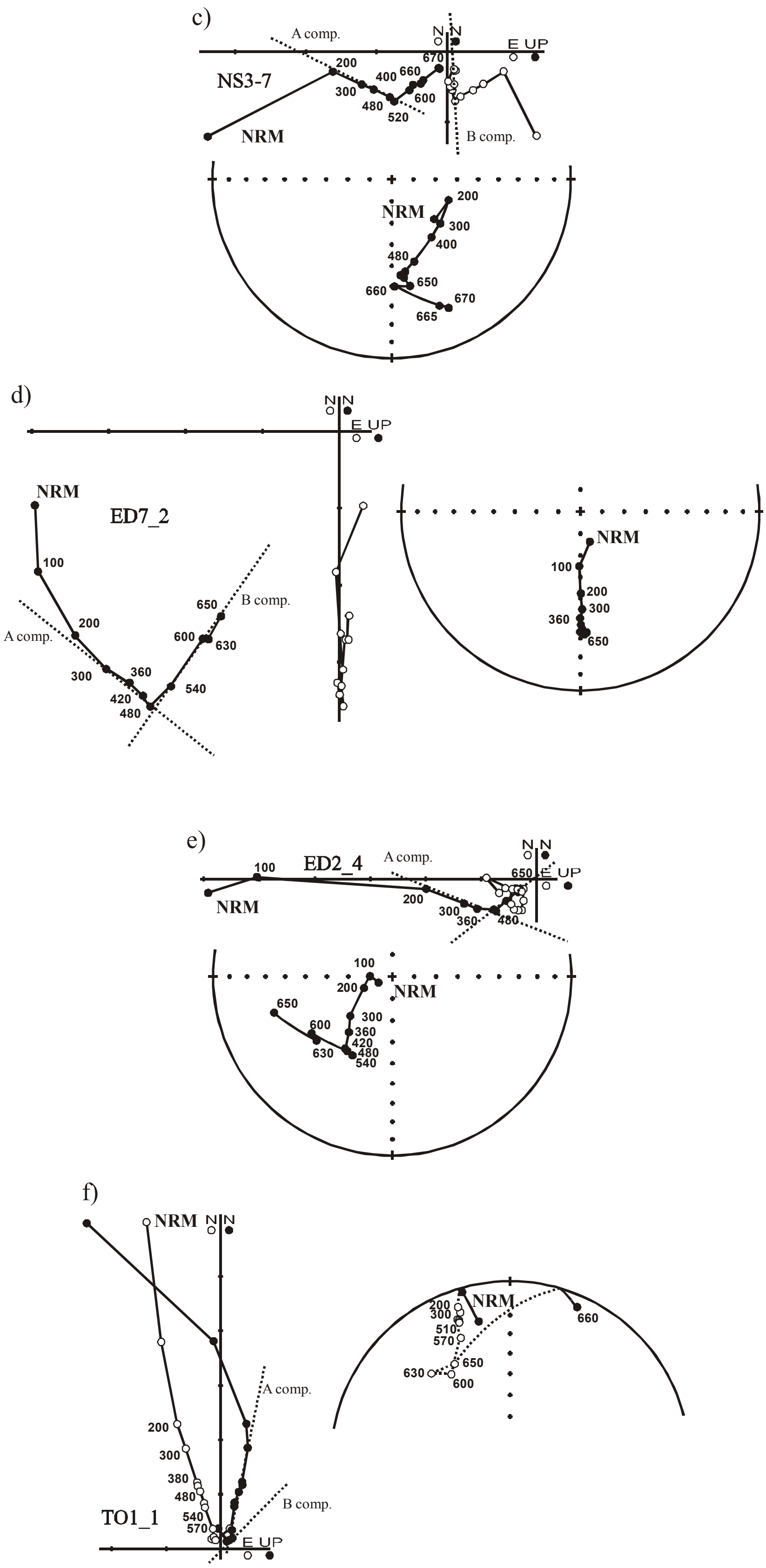


Figure 3.3. CTD.: Orthogonal plots of thermal demagnetization data.

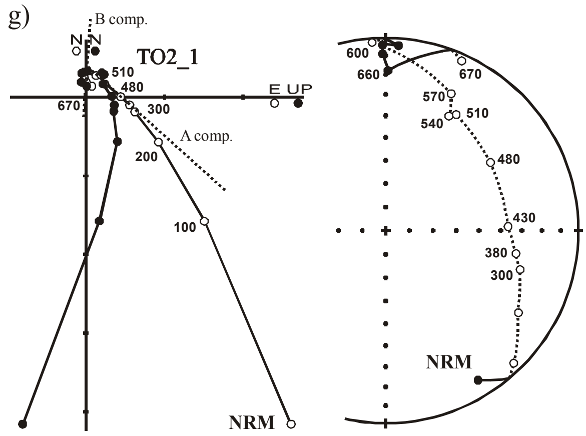


Figure 3.3. . CTD.: Orthogonal plots of thermal demagnetization data.

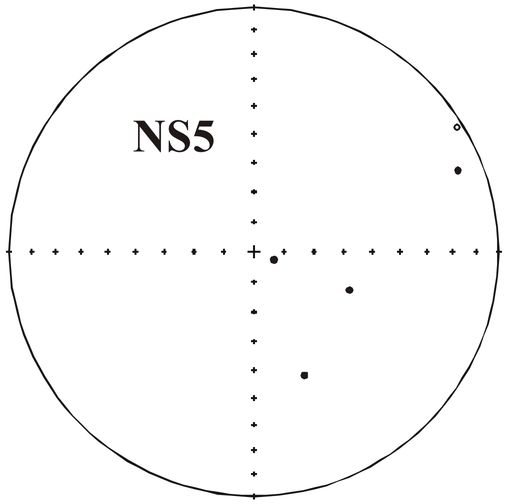


Figure 3.4. Characteristic remanence directions of magnetization for samples from site NS5. The data are shown in stratigraphic coordinates. Note the great scatter. Open (closed) symbols are upper (lower) hemisphere.

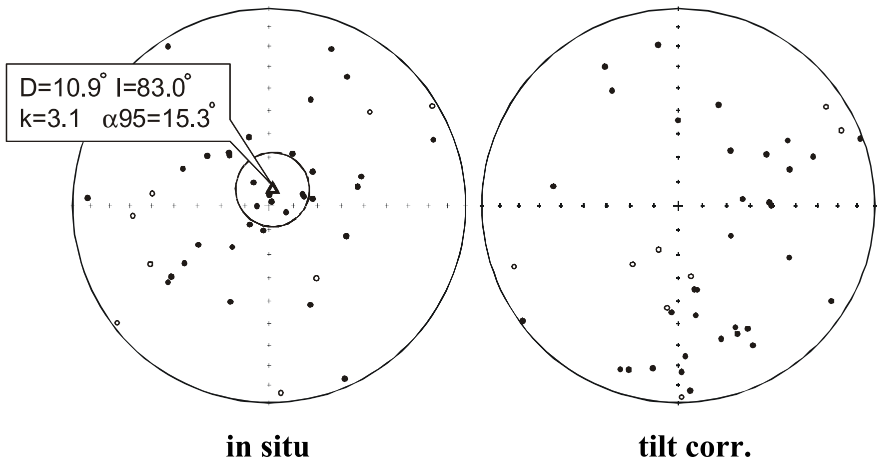


Figure 3.5. Distribution of component A for Silurian redbeds from NS locality on sample level.

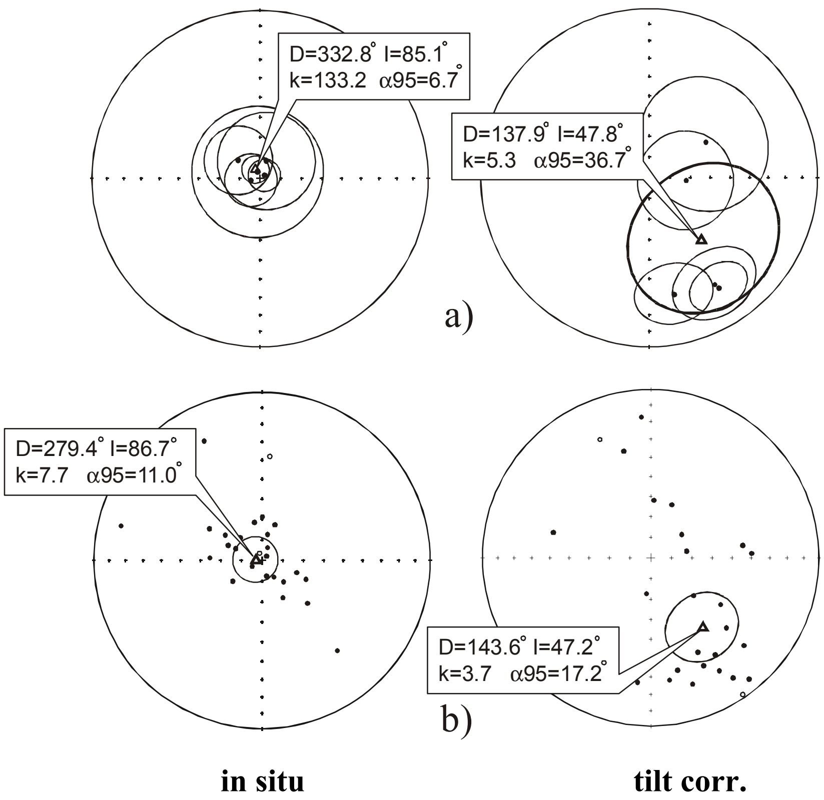


Figure 3.6. Distribution of components B with for Silurian redbeds from NS locality on (a) sites and (b) sample level.

The distribution of characteristic sample directions for component A, isolated in Lower Silurian red beds, sampled near the village of Dogolan (locality TO in Fig. 3.1), display the best grouping in geographic coordinates (Fig. 3.7, table 3.1 and 3.2) and is thus interpreted to be postfoldig in age. Component A is of reversed polarity and plots very closely to the Late Paleozoic reference direction based on the APWP of Baltica [Smethurst et al, 1998].

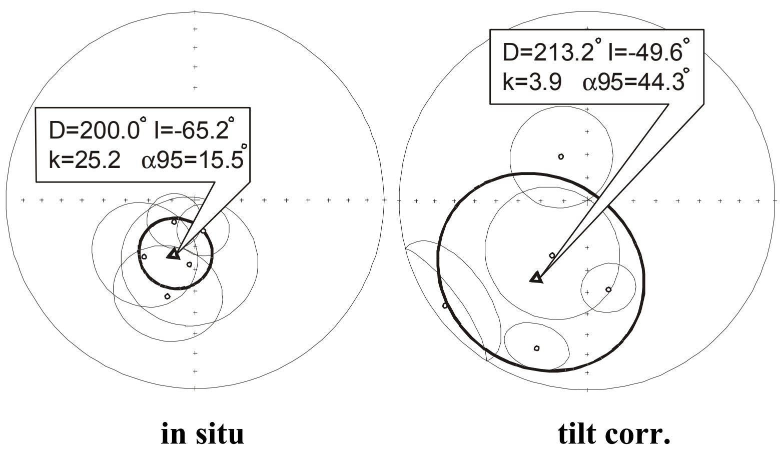


Figure 3.7. Site mean distribution of component A for Silurian redbeds from TO locality.

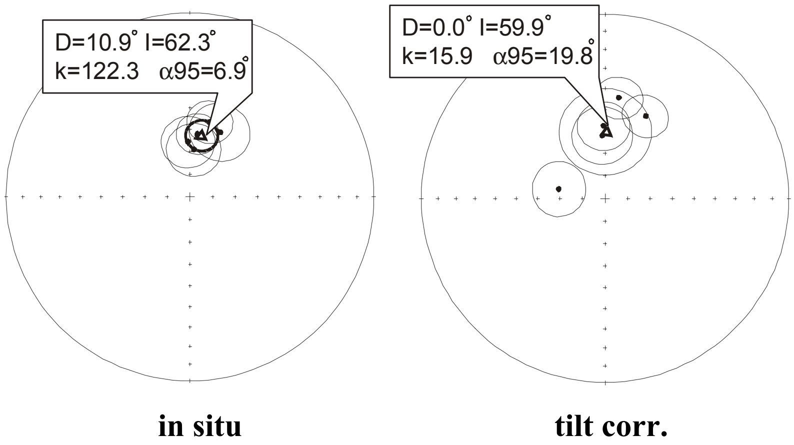


Figure 3.8. Site mean distribution of component A for Silurian redbeds from ED locality.

The direction of postfolding component A, isolated in Upper Devonian redbeds (locality ED) plots very close to the present day field direction (Fig 3.8, table 3.1 and 3.2). However, this direction is also situated on the trend of directions from Early Devonian to Permian obtained for South Kazakhstan. Therefore, the age of component A can be interpreted to be either of recent origin or Permo-Carboniferous in age. But as any drastic geological processes, which could have been the remagnetization process are unknown in this area, the interpretation that it is Late Paleozoic in age is preferred.

Table 3.1. Site – mean directions.

Site	Number of spec/	In situ				Tilt.corr.			
		D [°]	I [°]	k	α95 [°]	D [°]	I [°]	k	α95 [°]
Silurian redbeds									
NS locality									
Component A									
NS1	2	314.7	60.2	154.2	20.3	177.2	44.1	154.2	20.3
NS2	3	262.8	64.7	14.1	34.2	165.6	33.6	14.1	34.2
NS3	5	286.3	82.5	25.2	15.5	163.9	32.6	25.2	15.5
NS4	4	226.9	42.6	39.1	14.9	191.1	10.5	39.1	14.9
NS10	4	65.2	49.9	9.3	26.5	358.3	49.7	9.3	26.5
Mean (Site level Fig.4b)		**276.7**	**78.4**	**5.7**	**35.3**	**174.2**	**45.7**	**3.4**	**49.1**
Mean (Sample level Fig.4c)	**42**	**10.9**	**83.0**	**3.1**	**15.3**	**123.4**	**63.1**	**2.0**	**21.4**
Component B									
NS1	4	309.9	76.1	31.4	16.6	168.0	29.9	31.3	16.7
NS2+NS3	3	52.3	87.4	248.6	7.8	148.1	26.4	45.3	18.5
NS4	6	260.1	85.5	28.7	12.7	147.4	24.0	28.7	12.7
NS5	3	19.5	80.8	28.2	23.7	94.1	72.0	28.2	23.6
NS7	4	339.4	86.4	9.2	32.1	58.3	57.5	9.2	32.1
Mean (Site level Fig.4b)		**332.8**	**85.1**	**133.2**	**6.7**	**137.9**	**47.8**	**5.3**	**36.7**
Mean (Sample level Fig.4c)	**26**	**279.4**	**86.7**	**7.7**	**11.0**	**143.6**	**47.2**	**3.7**	**17.2**
TO locality									
Component A									
TO4	4	189.2	-46.3	18.2	22.1	322.5	-67.7	18.2	22.1
TO9	6	217.7	-77.4	33.2	11.8	192.2	-19.2	33.2	11.8
TO10	4	178.2	-62.4	11.1	28.8	206.7	-61.9	11.1	29.0
TO11	6	215.5	-57.0	9.7	22.7	226.8	-7.2	9.7	22.7
TO13	6	157.6	-76.6	36.7	11.2	159.2	-50.6	36.7	11.2
Mean		**200.0**	**-65.2**	**25.2**	**15.5**	**213.2**	**-49.6**	**3.9**	**44.3**
Upper Devonian redbeds (ED locality)									
Component A									
ED1	5	356.5	69.0	42.2	11.9	273.4	69.0	41.8	12.0
ED3	5	350.0	65.6	44.7	11.6	350.7	57.6	47.2	11.2
ED5	5	6.9	55.4	62.3	9.8	18.1	48.7	62.2	9.8
ED6	5	358.9	61.8	69.6	9.2	359.7	44.1	60.0	10.0
ED10	4	16.8	58.1	50.0	13.1	349.4	61.9	49.8	13.1
Mean		**10.9**	**62.3**	**122.3**	**6.9**	**352.0**	**59.9**	**15.9**	**19.8**

D - declination; I - inclination; k - precision parameter; α_{95} - radius of confidence circle (Fisher, 1953).

Table. 3.2. Obtained magnetic directions and virtual geomagnetic pole positions.

Locality	Age of rocks	Loc. Lat. [°N]	Loc. Long. [°E]	D [°]	I [°]	k	A95 [°]	Pol. Lat [°]	Pol. Long [°]	dp/dn [°]	φ [°]	Age of magnetization
NS	**Silurian and Lower Devonian**	**51°18'**	**74°19'**	**332.8**	**85.1**	**133.2**	**6.7**	**59.7**	**65.5**	**13.3/13.1**	**80.3 +9.7/-12.6**	**post Middle Devonian**
TO	**Silurian and Lower Devonian**	**49°35'**	**76°56'**	**200.0**	**-65.2**	**25.2**	**15.5**	**56.7**	**279.3**	**25.1/20.3**	**47.3 +24.6/-16.8**	**post Middle Devonian**
ED	**Upper Devonian**	**49°03'**	**67°49'**	**10.9**	**62.3**	**122.3**	**6.9**	**80.7**	**189.4**	**10.7/8.4**	**43.6 +9.2/-7.7**	**post Early Carboniferous**

Loc. Lat. and Loc. Long – the locality position; D - declination; I - inclination; k - precision parameter (Fisher, 1953); A95 - radius of confidence circle. Pol. Lat, Pol. Long and dp/dn are the latitude, longitude, and radius of 95% confidence circle of the paleopole, respectively; φ - paleolatitude.

3.4. Conclusions

1) Postfolding magnetizations were isolated for: a) Lower Silurian sedimentary rocks, sampled to the North of Karaganda (D=322.8°, I=85.1°, k=133.2, a95=6.7°), b) Lower Silurian sedimentary rocks from Chingiz-Nurbagai zone (D= 200.0°, I=-65.2°, k=25.2, a95=15.5°) and c) for the Upper Devonian rocks from Central Kazakhstan zone (D= 10.9°, I=62.3°, k=122.3, a95=9.6°). In case a) and b) the age of magnetization is post Middle Devonian. In the case c) it is post Early Carboniferous in age.

2) Postfolding directions, obtained for the Chingiz Range and Central Kazakhstan are in agreement with directions from South Kazakhstan.

Part 4

Paleotectonic history of Kazakhstan during the Paleozoic

Most paleogeographic reconstructions are based on the model that during Late Cambrian to Early Siluran times almost all cratons were situated in the southern hemisphere and moved slowly northward (Fig. 1.1). In this scenario, Siberia and Baltica were separated from East Gondwana by the Paleoasian Ocean [Didenko et al., 1994]. The history of this ocean began at least during the Vendian. Pre-cambrian ophiolite complexes represent evidence for the existence of this ocean in East Mongolia [Kepezhinskas and Kepezhinskas, 1991]. Since the Early Cambrian two gigantic submeridianal volcanic arc systems were formed [Pechersky and Didenko, 1995]. The first one along the edge of Siberia, and a second one along the edge of Gondwana. May Kazakhstan have been a part of the arc, separating the Paleoasian Ocean from Pantalassic ocean? Where was Kazakhstan in this time? In the follow chapter new and reliable paleomagnetic data will be projected in order to answer these questions.

4.1. Paleolatitude positions of Kazakhstan

For a critical analysis of Kazakhstan's change in palaeogographic position as a function of time, we used only paleomagnetic data obtained during the last 5 years. These data are based on studies by a team from the Russian Academy of Science [Bazhenov et al., 2003; Bazhenov et al., 2002; Collins et al., 2003; Levashova et al., 2003a] and by the Munich group [Alexyutin et al., in press; Alexyutin et al., 2003]. We note, however, that palaeomagnetic research has already been carried out in Kazakhstan by researchers from the Moscow Institute of Physics of the Earth [Grishin et al., 1991; Grishin et al., 1997; Pechersky and Didenko, 1995]. The data, however, are of various qualities and have not completely been demagnetized or show inconsistent directional behaviors. In addition, the majority of so-called prefolding directions are based on remagnetization circles, which are often only defined by the last two vector endpoints. That is why, these data will not be incorporated in our interpretation.

Most of the paleomagnetic results published during the last years, show a good agreement in the latitudinal position of Kazakhstan, Siberia and Baltica (Fig. 4.1). In the Late Cambrian, Baltica was situated in the southern hemisphere, whereas Siberia was situated in an equatorial position (Fig. 4.1). Since the Middle Ordovician, South Kazakhstan was situated a little bit to the North of Baltica and to the South of Siberia.

In the Early Silurian, Kazakhstan crossed the equator and then, as part of an ensemble of other big and small plates, it continued its hard way to the North until being accreted to Siberia and Baltica in the Permian. Presently, the resolution of the paleomagnetic data set available does not allow to identify differences in the latitudinal position of Kazakhstan, Baltica and Siberia during the Paleozoic.

Conclusions*:* a) since the Middle Ordovician there are no significant differences in the latitudinal position for both parts of Kazakhstan (South and North); b) most paleomagnetic data indicate that both parts of Kazakhstan were situated slightly further to the North as would be expected if Kazakhstan was a part of Baltica, and slightly further South then would be expected if Kazakhstan was a part of Siberia.

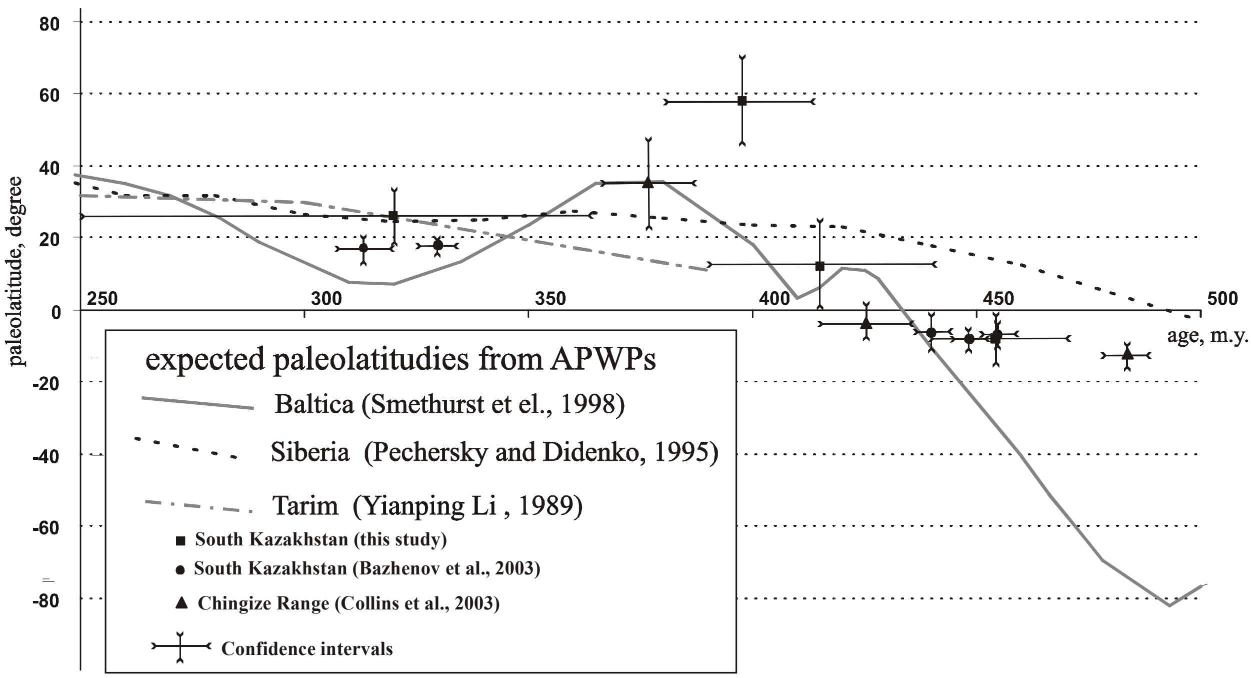


Figure 4.1. Observed paleolatitudes for Kazakhstan and expected palaeolatitudes as derived from the reference Apparent Polar Wander Paths from Baltica, Siberia and Tarim, recalculated for the location 43°N, 75°E.

Table 4.1 Paleomagnetic direction for Kazakhstan (rectangle 41°E to 52°E and 70°N to 80°N only). Selected from the Global Paleomagnetic Database (McElhinny, 1998, version 4.4).

№	AUTHORS	Ref. № in Database	Rock ages	PLACE	PLAT [°N]	PLONG [°E]
1	Pechersky,D.M. and Didenko,A.N., 1995	3045	377-391	Maikaner mulda, Central Kazakhstan	-4.9	279.2
2	Rusinov,B.S., 1986	2025	363-417	Central Kazakhstan	43.0	204.0
3	Grishin,D.V., et al., 1991	2594	363-417	Central Kazakhstan	58.0	208.0
4	Grishin,D.V., et al., 1991	2594	377-417	Chingiz-Tarbagay anticlinorium, Central Kazakhstan	-5.0	295.0
5	Pechersky,D.M. and Didenko,A.N., 1995	3045	377-417	Arkalyk mountain, Central Kazakhstan	-10.7	87.2
6	Grishin,D.V., et al., 1991	2594	363-417	Chingiz-Tarbagay anticlinorium, Central Kazakhstan	26.0	297.0
7	Pechersky,D.M. and Didenko,A.N., 1995	3045	391-417	Zhalair Range, Yalta Village, Central Kazakhstan	-6.8	316.0
8	Pechersky,D.M. and Didenko,A.N., 1995	3045	419-428	Zhanbazar,Ulken-Dogolan Mtns., Central Kazakhstan	26.2	297.2
9	Pechersky,D.M. and Didenko,A.N., 1995	3045	423-458	Tkenekty and Ushkyzyl Mtns., Central Kazakhstan	-20.5	52.8
10	Grishin,D.V., et al., 1991	2594	428-458	Central Kazakhstan	-21.0	63.0
11	Turmanidze,T.L., 1991	2852	428-470	Pirnozar, Ushkizi and Tkenekty Mountains, M.Kazakhstan	-16.0	44.8
12	Grishin,D.V., et al., 1991	2594	443-458	Maykain-Kyziltas zone, Central Kazakhstan	-8.0	146.0

Table 4.1. CTD.: Paleomagnetic direction for Kazakhstan (rectangle 41°E to 52°E and 70°N to 80°N only). Selected from the Global Paleomagnetic Database (McElhinny, 1998, version 4.4)**.**

13	Grishin,D.V., et al., 1991	2594	443-458	Chingiz-Tarbagay anticlinurium, Central Kazakhstan	38.0	264.0
14	Turmanidze,T.L., et al., 1991	2626	449-458	Middle Kazakhstan	-21.0	95.0
15	Pechersky,D.M. and Didenko,A.N., 1995	3045	443-470	Chingiz-Tarbagatay anticlininorium, Central Kazakhstan	-39.0	78.3
16	Grishin,D.V., et al., 1991	2594	458-470	Central Kazakhstan	-22.0	51.0
17	Grishin,D.V, at al., 1991	2594	458-470	Chingiz-Tarbagay anticlinurium, Central Kazakhstan	39.0	251.0
18	Turmanidze,T.L., et al., 1991	2626	458-470	Middle Kazakhstan	-30.0	60.0
19	Turmanidze,T.L., et al., 1991	2626	458-470	Middle Kazakhstan	-18.0	103.0
20	Grishin,D.V., et al., 1991	2594	458-470	Maykain-Kyziltas zone, Central Kazakhstan	-14.0	150.0
21	Pechersky,D.M. and Didenko,A.N., 1995	3045	458-470	Itmurundy and Ushtogan Mtns., Kazakhstan	-24.7	50.1
22	Pechersky,D.M. and Didenko,A.N., 1995	3045	443-495	Karaulcheku Allochton, Central Kazakhstan	-21.4	95.5
23	Grishin,D.V., et al., 1991	2594	458-495	Central Kazakhstan	9.0	347.0
24	Grishin,D.V., et al., 1991	2594	458-495	Central Kazakhstan	-22.0	61.0
25	Pechersky,D.M. and Didenko,A.N., 1995	3045	458-495	Agyrek Mountain, Central Kazakhstan	-11.1	149.0
26	Pechersky,D.M. and Didenko,A.N., 1995	3045	458-495	Tolpak Mountain, Central Kazakhstan	-18.1	103.0
27	Bazhenov et al., 2003	n/a	Bashkirian	South Kazakhstan	53.8	202.1

Table 4.1. CTD.: Paleomagnetic direction for Kazakhstan (rectangle 41°E to 52°E and 70°N to 80°N only). Selected from the Global Paleomagnetic Database (McElhinny, 1998, version 4.4)**.**

28	Bazhenov et al., 2003	n/a	Visean-Serpukhovian	South Kazakhstan	61.6	287.2
29	Bazhenov et al., 2003	n/a	Ashgillian	South Kazakhstan	37.4	281.1
30	Bazhenov et al., 2003	n/a	Late Caradocian	South Kazakhstan	38.2	246.5
31	Bazhenov et al., 2003	n/a	Early Tremadoc	South Kazakhstan	31.1	214.7
32	Levashova et al. , 2003a	n/a	Middle Devonian	Chingiz Range	-11.3	85.1
33	Levashova et al. , 2003a	n/a	Early Silurian	Chingiz Range	-33.6	32.7
34	Collins et al. , 2003	n/a	Early Ordovician	Chingiz Range	-43.9	127.8
35	Collins et al. , 2003	n/a	Late Cambrian	Chingiz Range	-27.0	168.2
36	This study, DUL and AND localities (see table 1.2.)	n/a	post Middle Devonian	South Kazakhstan	65.6	265.8
37	This study, DUL and AND localities (see table 1.2.)	n/a	Silurian to Early Devonian	South Kazakhstan	56.7	279.3
38	This study, GEO locality (see table 1.2.)	n/a	post Late Ordovician	South Kazakhstan	59.8	174.6
39	This study, AGA locality (see table 1.2.)	n/a	post Late Ordovician	South Kazakhstan	38.3	145.3
40	This study, AGA locality (see table 1.2.)	n/a	Early to Late Ordovician	South Kazakhstan	37.7	243.3
41	This study, MIN and SAR localities (see table 2.2.)	n/a	Post Early Carboniferous	South Kazakhstan	78.1	162.4
42	This study, ESP locality (see table 2.2.)	n/a	Post Early Carboniferous	South Kazakhstan	66.7	230.0
43	This study, OTA and ODA localities (see table 2.2.)	n/a	Early Carboniferous - Triassic	South Kazakhstan	31.7	158.2
44	This study, KHA and SAR localities (see table 2.2.)	n/a	post Middle Devonian	South Kazakhstan	67.0	139.9
45	This study, KOK and AND localities (see table 2.2.)	n/a	post Middle Devonian	South Kazakhstan	78.3	209

Table 4.1. CTD.: Paleomagnetic direction for Kazakhstan (rectangle 41°E to 52°E and 70°N to 80°N only). Selected from the Global Paleomagnetic Database (McElhinny, 1998, version 4.4)**.**

46	This study, KOK and AND localities (see table 2.2.)	n/a	Early - Middle Devonian	South Kazakhstan	72.9	55.4
47	This study, NS locality (see table 3.2.)	n/a	post Middle Devonian	North Kazakhstan	59.7	65.5
48	This study, TO locality (see table 3.2.)	n/a	Silurian to Early Devonian	North Kazakhstan	56.7	279.3
49	This study, ED locality (see table 3.2.)	n/a	post Late Ordovician	Central Kazakhstan	80.7	189.4

PLat, PLong - latitude and longitude of the paleopole.

4.2. Rotations relatively to Baltica and Siberia

All paleomagnetic data from South and Central Kazakhstan indicate a relative rotation of up to 80° (w.r. to Baltica) and 140° (w.r. to Siberia) (Fig. 4.2). Most part of this rotation happened during Devonian –Permian time. This implies that during this time, south Kazakhstan was separated from both Baltica and Siberia.

For the Chingiz Range there does not exist any reliable paleomagnetic data. The most reliable result obtained so far (Levashova et al., 2003a) from Silurian volcanic rocks from the Chingiz Range, is in good agreement with expected Silurian inclinations for South Kazakhstan (D ≈ 330-340°, I ≈ 0°, assuming normal polarity). Expected, because there are no Silurian results from South Kazakhstan so far, and consequently only by interpolation between Ordovician and Early Devonian the Silurian inclination can be calculated. The Silurian result from the Chingiz Range has a declination of 216.5, which is supposed to be of normal polarity [Bazhenov et al., 2003]. The reason for normal polarity choice was a paleomagnetic result for Devonian rocks from the same area (D=352.4°, I= -49.3°, [Levashova et al., 2003b]). The primary character of these data (obtained from basalts) is not supported by any field test and only the rectilinear decay of the magnetization towards the origin of the projection and the remoteness from late Paleozoic overprints and any expected post-Paleozoic field directions can be used to speculate about the character of magnetization. Therefore, this result is not reliable enough and it cannot be ruled out that the declination of 216° identified in the Silurian rocks from the Chingiz Range might represent negative polarity. In this case the angle of bending of the Kazakhstan belt is not more then 60°, in contrast to the conclusions of Bazhenov et al., (2003), who suspected more than 180 degrees. But, only new paleomagnetic results from Chingiz Range can help to solve those problems.

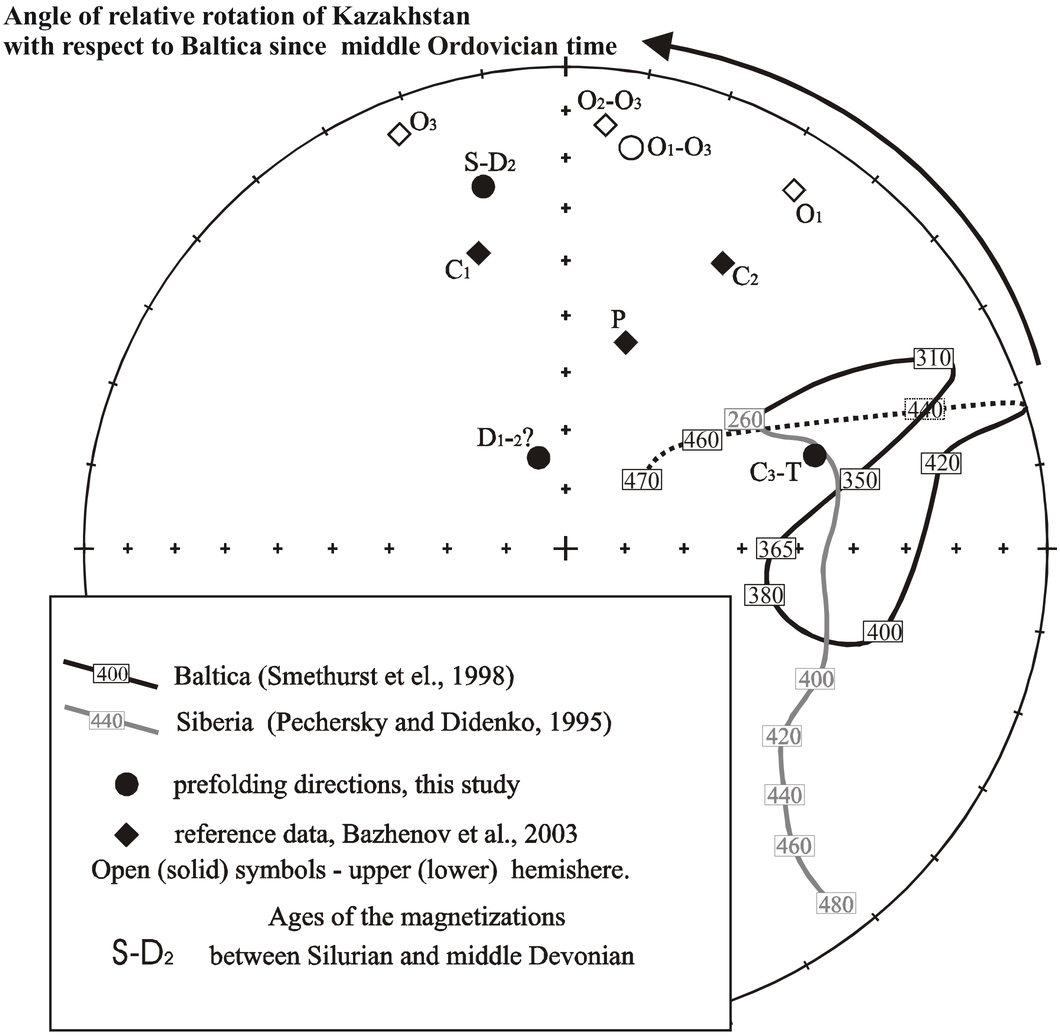
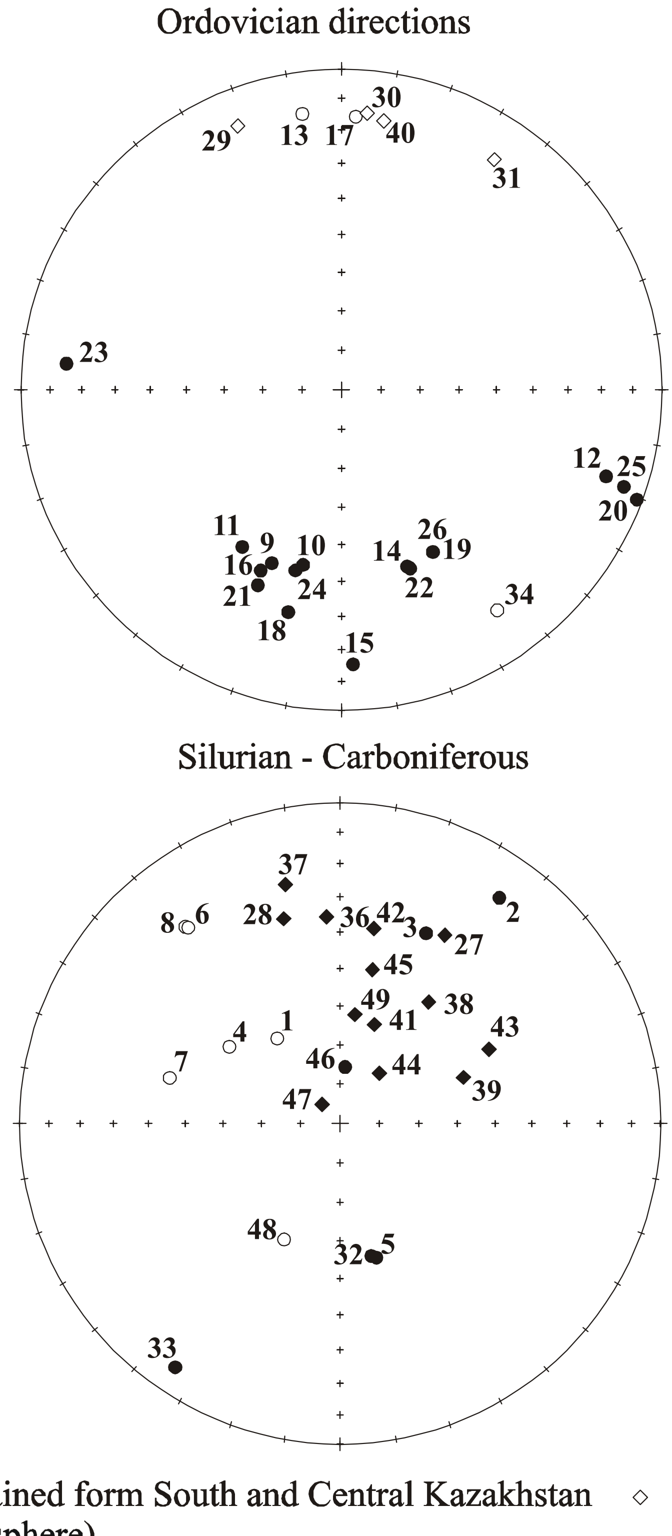


Figure 4.2. Comparison of paleomagnetic directions obtained from Central Kazakhstan and South Kazakhstan with reference directions, calculated from APWPs of Baltica [Smethurst et al., 1998] and Siberia [Pechersky and Didenko, 1995].



Directions, obtained form South and Central Kazakhstan ◇ upper,
◆ lower hemisphere)

Directions, obtained form Nourth Kazakhstan ○ upper, ● lower hemisphere)
1,2.....49 - see numbers in table 3

Figure 4.3. Comparison of all paleomagnetic directions obtained from Central, North and South Kazakhstan.

4.3. The Apparent Polar Wander Path of Kazakhstan

The construction of an Apparent Polar Wander Path (APWP) is the heart of classic paleotectonic reconstructions based on paleomagnetic data. Khramov et al., 1982, were the first to suggest an APWP for Kazakhstan. This APWP, however, was based on old paleomagnetic results, obtained with outdated paleomagnetic methods (table 4.2.).

Table 4.2. The APWP of Kazakhstan after Khramov et al., (1982). P_2: Late Permian, P_1: Early Permian, C_2: Mid Carboniferous, C_1: Early Carboniferous, D_3: Upper Devonian. K and α95 are statistical parameters (Fisher, 1953).

Age	Pol. Lat [°N]	Pol. Long [°E]	k	α95	Data points
P_2	54	169	-	-	-
C_2-P_1	54	167	46	10	4
C_1	69	201	1250	4	3
D_3	56	193	-	-	-

Presently, only a few prefolding directions exist for South Kazakhstan and only one reliable direction for North Kazakhstan (Chingiz Range). We are still too far from compiling a reliable APWP curve for Kazakhstan. However, even a preliminary APWP will be very important, as it will provide important constraints for paleotectonic reconstruction in this area.

Due to the small number of prefolding directions, practically each result corresponds to a paleopole position for its time frame. Only for the Middle Ordovician interval two results are available. They have been averaged.

Lower Ordovician to Middle Devonian pole positions follow a loop from the Southern part of Africa to the mid of the Indian Ocean. Then the APWP curve swings to the South and subsequently to the East up to the position of Early – Middle Devonian paleopole. The next reliable point of the APWP is the Upper Devonian – Early Carboniferous paleopole. At last, Permian paleopoles are situated in the same area as the paleopoles for Baltica and Siberia (Fig. 4.4).

Paleopoles, calculated from postfolding directions may be divided into two groups. Paleopoles from the first group are situated on (or close to) the suggested APWP and thus support it. The second group consists of directions with very steep inclinations. These paleopoles are situated close to the Triassic paleopole for Eurasia and might reflect a Mesozoic remagnetization event.

Of course, the suggested APWP of South Kazakhstan is still too far to be reliable and more paleomagnetic results are needed to make it more precise.

Table 4.3. Observed paleopoles from South and Central Kazakhstan (see tables 1.2, 2.2, 3.2 and 4.1). O: Ordovician, S: Silurian, D: Devonian, C: Carboniferous, T: Triassic, 1: Early, 2: Mid, 3: Late.

reference	**Age of magnetization**	**Pol. Lat [°]**	**Pol. Long [°]**
Prefolding directions			
Bazhenov et al., 2003	O_1	31.1	214.7
Bazhenov et al., 2003	O_{2-3}	38.2	246.5
This study, AGA locality (see table 1.2.)	O_1-O_3	37.7	243.3
Bazhenov et al., 2003	O_3	37.4	281.1
This study, DUL and AND localities (see table 1.2.)	S-D_2	56.7	279.3
This study, KOK and AND localities (see table 2.2.)	D_1-D_2	72.9	55.4
Bazhenov et al., 2003	C_1	61.6	287.2
Bazhenov et al., 2003	C_2	53.8	202.1
This study, OTA and ODA localities (see table 2.2.)	C_1-T	31.7	158.2
Postfolding directions			
This study, ED locality (see table 3.2.)	$<C_1$	80.7	189.4
This study, MIN and SAR localities (see table 2.2.)	$<C_1$	78.1	162.4
This study, ESP locality (see table 2.2.)	$<C_1$	66.7	230.0
This study, KHA and SAR localities (see table 2.2.)	$<D_2$	67.0	139.9
This study, KOK and AND localities (see table 2.2.)	$<D_2$	78.3	209
This study, DUL and AND localities (see table 1.2.)	$<D_2$	65.6	265.8
This study, AGA locality (see table 1.2.)	$<O_3$	38.3	145.3
This study, GEO locality (see table 1.2.)	$<O_3$	59.8	174.6

Table 4.4. The APWP of South Kazakhstan based on paleomagnetic results from the last decade. O: Ordovician, S: Silurian, D: Devonian, C: Carboniferous, T: Triassic, 1: Early, 2: Mid, 3: Late.

reference	**Used data**			**APWP**		
	Age of magnetization	**Pol. Lat [°]**	**Pol. Long [°]**	**Age**	**Pol. Lat [°]**	**Pol. Long [°]**
Bazhenov et al., 2003	O_1	31.1	214.7	O_1	31.1	214.7
Bazhenov et al., 2003	$O_{2\text{-}3}$	38.2	246.5	O_2	38	244.9
This study, AGA locality (see table 1.2.)	O_1-O_3	37.7	243.3			
Bazhenov et al., 2003	O_3	37.4	281.1	O_3	37.4	281.1
This study, DUL and AND localities (see table 1.2.)	S-D_2	56.7	279.3	S-D_2	56.7	279.3
This study, KOK and AND localities (see table 2.2.)	D_1-D_2	69.3	76.8	D_1-D_2	69.3	76.8
Bazhenov et al., 2003	C_1	61.6	287.2	C_1	61.6	287.2
This study, OTA and ODA localities (see table 2.2.)	C_1-T	31.7	158.2	P	31.7	158.2

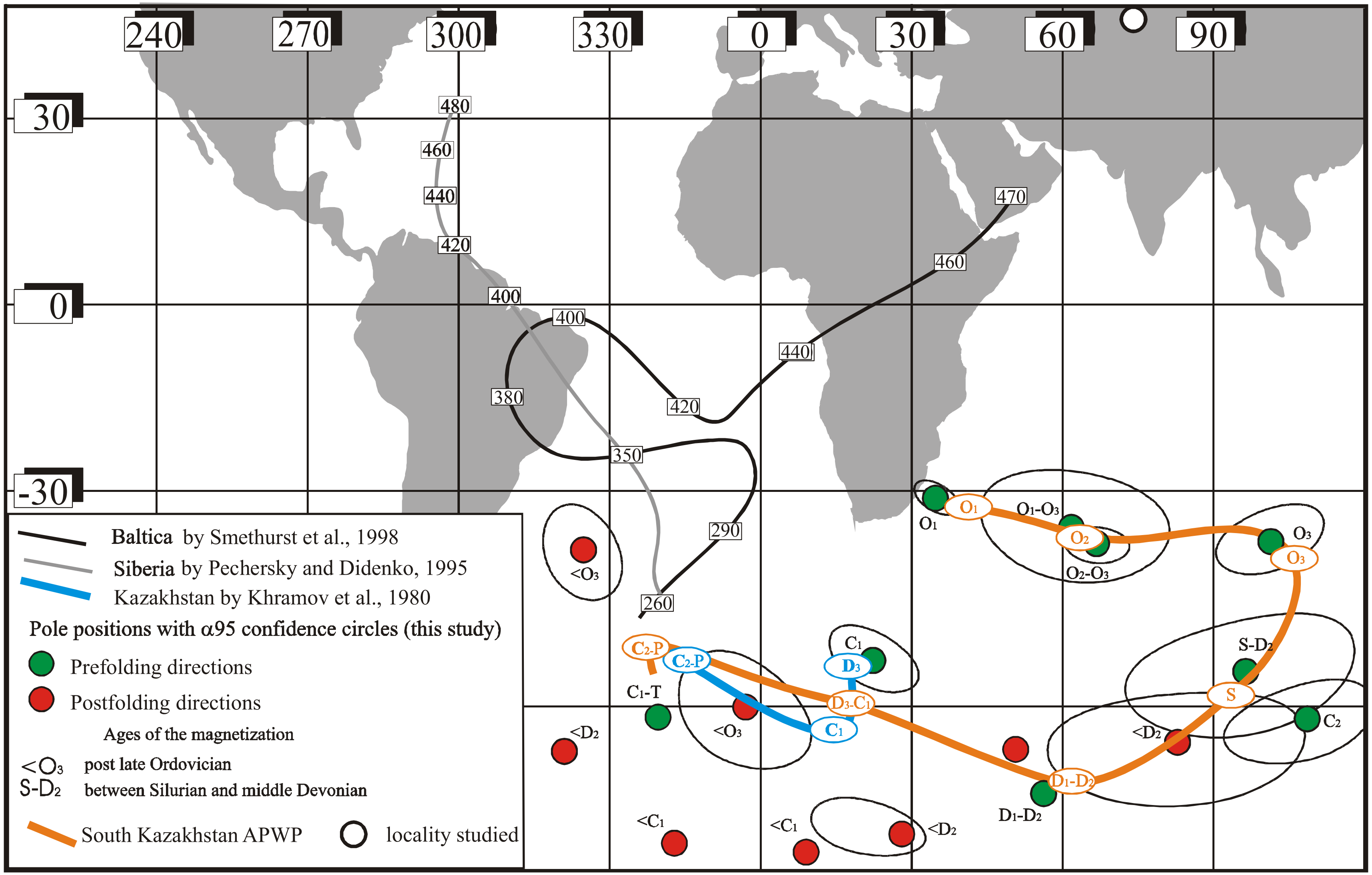


Figure 4.4. APWP for South Kazakhstan

4.4 Testing tectonic models for the evolution of Kazakhstan

New paleomagnetic data can be used to test existing Paleozoic paleotectonic models for Kazakhstan.

Among the competing models for the evolution of Kazakhstan, two lines of thought can be identified. (a) Kazakhstan is a mosaic of microplates and island arcs, amalgamated by the Latest Ordovician and positioned in low northerly latitudes throughout the Paleozoic [Didenko et al., 1994] or (b) Kazakhstan was formed during continuous accretion of volcanic arcs along the Kipchak Arc moving from a Southerly position into Northerly latitudes throughout the Paleozoic [Sengör and Natal'in, 1996].

The polarity option for the Early Paleozoic results allows for two competing drift scenarios for this time. If we suppose normal polarity for negative inclinations, then we are compelled to place Kazakhstan's units into the Southern hemisphere of the Earth, as Sengör and Natal'in (1996) proposed. If we suppose a reversed polarity for the negative inclinations, then we are compelled to place Kazakhstan's units into the northern hemisphere of the Earth, as Didenko et al. (1994) proposed.

Here, I support the Sengör and Natal'in point of view – South Kazakhstan was situated in the Southern hemisphere in Cambrian to Ordovician times. The reason for this is - as it was shown in Part1 and Part2 - that there is a continuous trend of paleomagnetic directions from the Permian to the Ordovician, based on the assumption of negative Ordovician inclinations representing normal polarity.

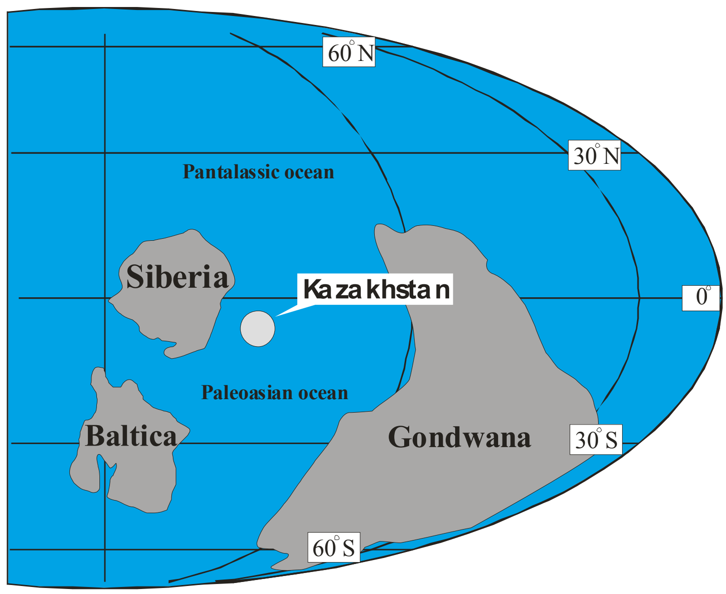


Figure 4.5. Schematic position of Kazakhstan in the Lower Paleozoic.

However, paleomagnetic rotations observed for South Kazakhstan cannot be reconciled with tectonic models such as the one for the evolution of the Kipchak arc [Sengör et al., 1993; Sengör and Natal'in, 1996]. This model assumes the existence of an Early Paleozoic volcanic arc, which extended from Baltica in the South to Siberia in the North with the edges of the arc being tied to these two cratons. The suggested geometry of the original arc puts very strict kinematic constrains on relative motions and rotations of individual blocks within the Kipchak Arc. In particular, it implies, that since the Early Devonian southern Kazakhstan had experienced clockwise rotation of about 90° relative to Baltica and about 30° clockwise rotation with respect to Siberia ([Sengör and Natal'in, 1996], Fig. 4.6). This is in contrast to paleomagnetic results [this study, Bazhenov, et al, 2003] indicating counterclockwise rotation.

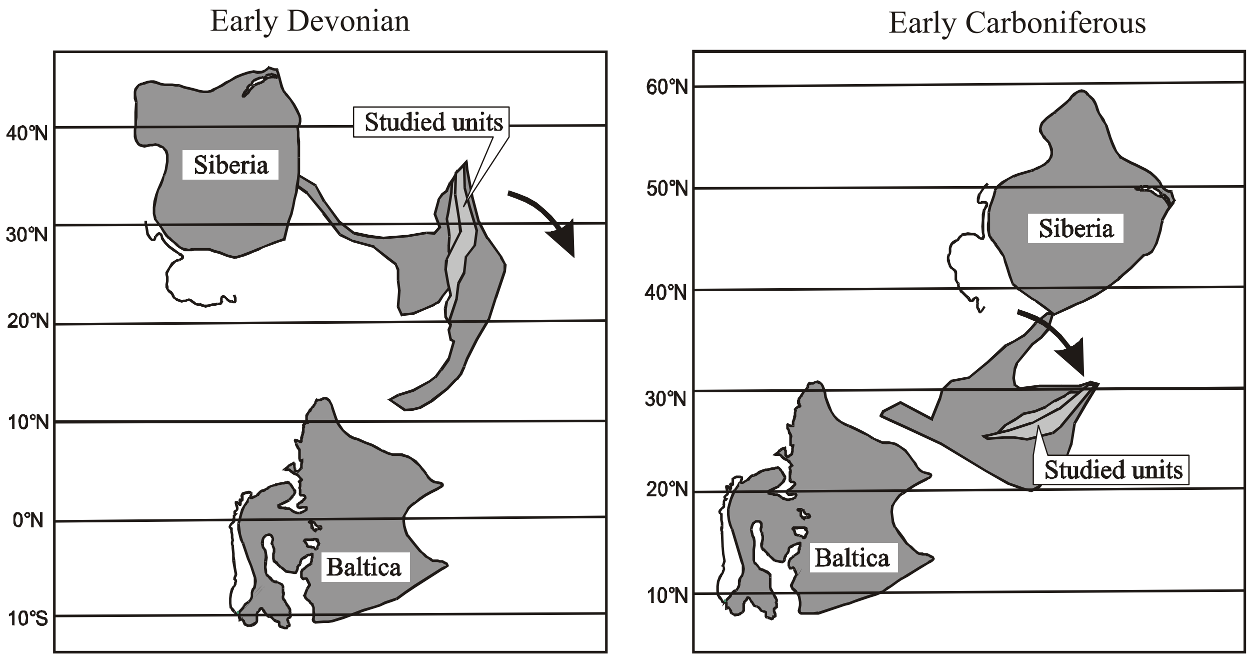


Figure 4.6. Clockwise rotation of Kazakhstan according to the model of the Kipchak arc (simpled after Sengör and Natal'in, 1996).

4.5. Remagnetization events

Widespread regional if not continental scale remagnetization events are a well-known phenomenon in paleomagnetism (see for example Zwing et al., 2002). As a rule of thumb, remagnetization events are of extremely short duration and can in general be linked to orogenic processes. Nevertheless, the physical and/or chemical processes causing remagnetization are not well understood yet [Zwing et al., 2002]. Paleomagnetic studies on Early and Mid Paleozoic rocks from Southern Kazakhstan and the Northern Tian Shan report postfolding magnetizations with directions similar to Permian direction for the area [this study, Bazhenov, et al, 2003]. Consequently, the overprint magnetizations were interpreted to be Permian in age and associated with widespread remagnetization during the Kiaman Geomagnetic Superchron [Bazhenov et al., 2003; Collins et al., 2003; Levashova et al., 2003a]. Postfolding paleomagnetic data obtained in this study, however, reveal a much more complicated directional pattern (table 4.3, Fig. 4.7), and indicate several distinct remagnetization events of different age. This conclusion is based on the fact that the postfolding directions identified here, differ significantly from the Permian reference direction derived from either the apparent polar wander path for Baltica or Siberia. On the other hand, it is clear that Kazakhstan was amalgamated to Baltica by the Permian. In addition, several cases have been identified where normal as well as reversed magnetic polarities have been isolated (table 4.3, Fig. 4.7). This again is a strong argument against a single remagnetization event during the Carboniferous and Permian time (Kiaman Geomagnetic Superchron), which is characterized by exclusively inverse polarity of the Earth magnetic field [Opdyke, 1995]. Since the mean inclination values for the secondary component of magnetization are rather shallow, a Mesozoic age can be ruled out based on the expected reference directions. It is, therefore argued, that the remagnetization occurred most likely before the Late Carboniferous. This interpretation is supported by the observation that the resulting paleopole positions plot on the Paleozoic segment of the APWP of Kazakhstan [Alexyutin et al., in press; Bazhenov et al., 2003]. It cannot be excluded that the area was also affected by Permian remagnetization events; however, it is believed that this happened only as minor event.

Table. 4.3. Overprint directions from South Kazakhstan in comparison with the Permian reference direction.

Locality	Age of rocks	D	I	k	$\alpha95$	Polarities	Age of overprint	Reference
NS	D_{1-2}	332.8	85.1	133.2	6.7	normal	post D_2	this study, part3
TO	S	200.0	-65.2	25.2	15.5	negative	post D_2	this study, part3
ED	D_3	10.9	62.3	122.3	6.9	normal	post C_1	this study, part3
MIN, SAR	C_1	197.0	-63.4	51.1	10.8	both	post C_1	this study, part2
ESP	D_3-C_1	190.4	-38.6	71.8	7.2	negative	post C_1	this study, part2
KHA	D_{1-2}	33.1	66.6	18.5	11.5	both	post D_2	this study, part2
AND, KOK	D_1	10.4	54.8	7.2	26.8	both	post D_2	this study, part2
DUL, AND	S-D_1	355.5	35.6	18.1	9.6	both	post D_2	this study, part1
GEO	O_2	215.7	-51.3	55.4	5.9	negative	post O_3	this study, part1
AGA	O_{1-2}	249.7	-57.3	230.4	5.1	negative	post O_3	this study, part1
Permian reference direction for locality 43.0° N,74.5° E		233.9	-54.3			negative	260 m.y.	From Smethurstet al., [1998]

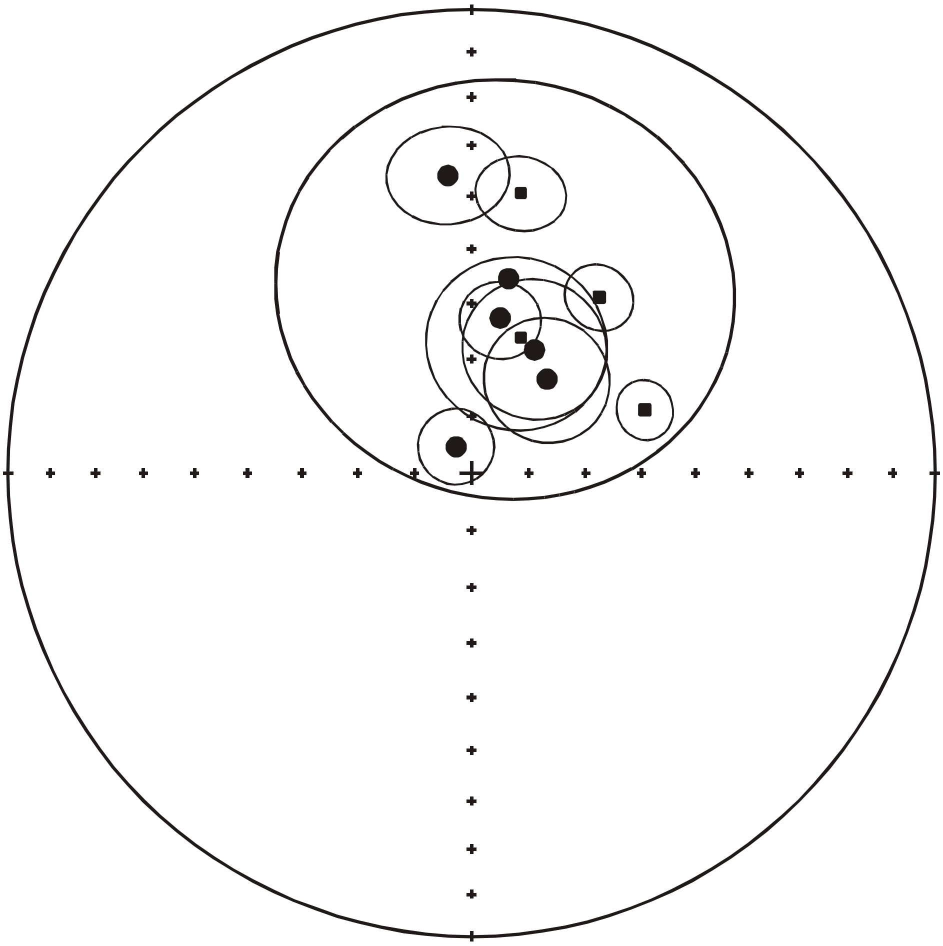


Figure 4.7. Overprint directions from south Kazakhstan. Circles - directions, which have normal (or both) polarities, squares - directions with only reversed polarity (table 4.3).

4.6. Orocline or Triple Junction?

During the last decade the "orocline" [Carey, 1955] model became very popular among the geological community. Oroclines are large scale structures which have been bent by rotation about near vertical axes. In the past, paleomagnetism has proven to be very efficient in demonstrating secondary oroclinal bending. The orocline concept has become accepted when it became evident that tectonic plates are not rigid and can react to deformation by internal rotation and/or translation. The question which remains to be answered, yet, is to what extent large scale curved structures represent true oroclinal (secondary) bending. Can large scale curved structures in orogens be of secondary origin [Eldredge et al., 1985; Bachtadse and Van der Voo 1986]? In the following these questions will be discussed in detail on the basis of paleomagnetic data for Kazakhstan.

The question in the center of the debate is whether the Kazakhstan Devonian volcanic belt has been bent during secondary deformation or has been bent originally. A bent structure is of primary origin if the coeval paleomagnetic directions, obtained all over he belt are independent of the regional strike. However, if variations in declination are controlled by variations in strike, a secondary character of the structure has to be postulated.

I would like to discuse a viable alternative and postulate the existence of a triple junction [Filippova et al., 2001] at the intersection of North and Central Kazakhstan. This model could explain the horseshoe shape of the Kazakhstan volcanic belt without secondary bending.

Based on previous reconstructions [Filippova et al., 2001; Pechersky and Didenko, 1995; Sengör and Natal'in, 1996; Zonenshain et al., 1990a] and paleomagnetic data [Collins et al., 2003; Bazhenov et al., 2003; Levashova et al., 2003a, this study], we propose the following scenario of tectonic evolution for the studied area.

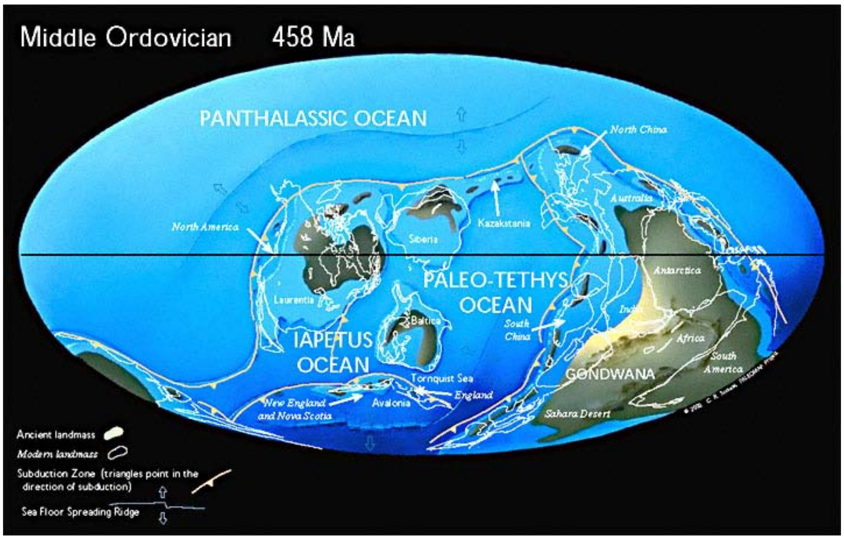


Figure 4.8. Global reconstruction for the Middle Ordovician time (http://www.scotese.com).

Most of the continental units in Early Paleozoic were situated in the Southern hemisphere of the planet. The Northern hemisphere was occupied by oceanic crust (Pantalassic Ocean). In the studied region the situation was defined by the interaction of several tectonic plates – Baltica, Siberia and the oceanic Paleopacific plate (or plates). Remnants of the latter are seen in the different accrecional complexes, most of them in North Kazakhstan. The structures of South Kazakhstan could be a part of the boundary of Baltica and structures of North Kazakhstan (Chingiz Range) could be a part of the boundary of Siberian plate. Note, that some researchers [Kurchavov, 1994] stretch the volcanic Devonian belt to the North from the East end of Central Kazakhstan segment, but not to the East (to Chingiz Range). Subduction of the oceanic plates under South Kazakhstan and the Chingiz Range took place in this time. The boundary between Baltica and Siberia was probably also of subduction type.

Of course, the characters of plate boundaries are depending on the kinematics parameters of the plates. It means that, sometime the subduction might change by the transform movement or even by the extention.

In general, this model supposes primary bent shape for Kazakhstan structures. A lot of bent looking structures are known in the present day plate configurations. For instance, Kamchatka peninsula and Aleutian islands on the boundary Eurasian and Pacific plates (Fig.4.9).

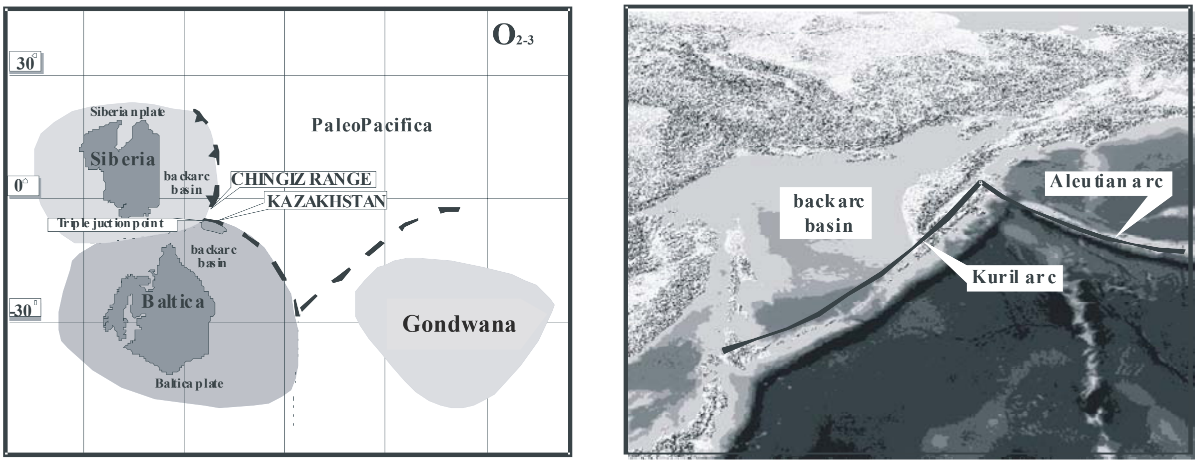


Figure 4.9. Triple junction model for the evolution of Kazakhstan (Middle-Late Ordovician time frame) and the present day analogs.

All latest tectonic history of Kazakhstan is the result of relative movement between Baltica and Siberia. In the Middle Paleozoic Baltica and Siberia moved to the North and in the same time have been subjected by clockwise rotation (Fig. 4.6). The rotational rate of Siberia being faster then that of Baltica, coused closure of PaleoUral Ocean forming part of the Pantalassic (Fig. 4.9-13).

As it has been shown above, paleomagnetic data indicate anticlockwise rotation of the South Kazakhstan reference Baltica and Siberia. Most part of this rotation happened during Devonian – Permian time. This is in very good agreement with suggested models. Starting in Late Silurian – Early Devonian times Baltica had been subjected to clockwise rotation. As a result of this rotation, a backarc basin opened between Baltica and South Kazakhstan. Traces of this basin may be obtained to the North-East of Kazakhstan, in the south Mugogar area, where Devonian dike swarms are know [Pechersky and Didenko, 1995]. According to geological data the Mugogar basin had been opened in Devonian times.

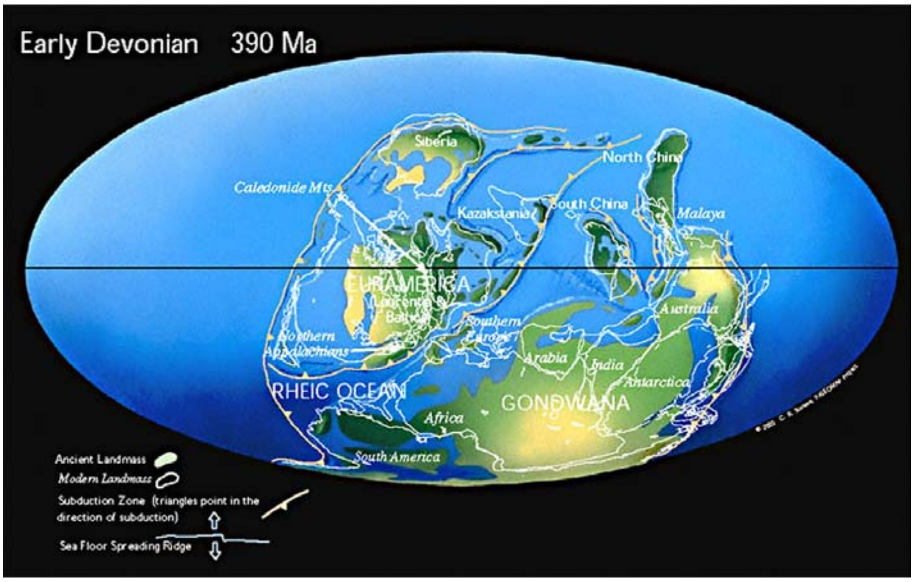
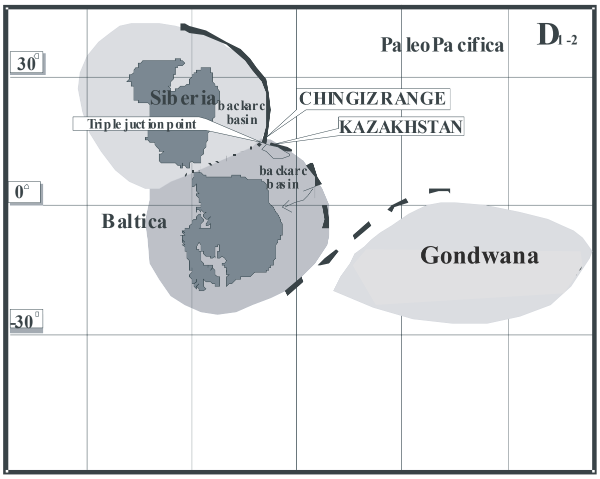


Figure 4.10. Global reconstruction for the Early Devonian (http://www.scotese.com).



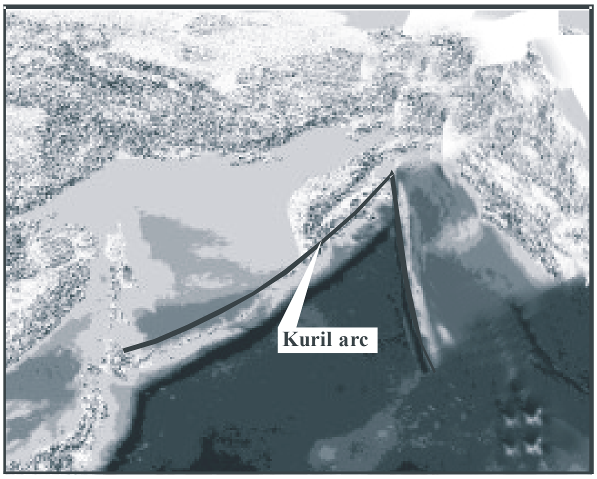


Figure 4.11. Triple junction model for the evolution of Kazakhstan (Devonian time frame) and possible way of evolution for the Circum Pacific region.

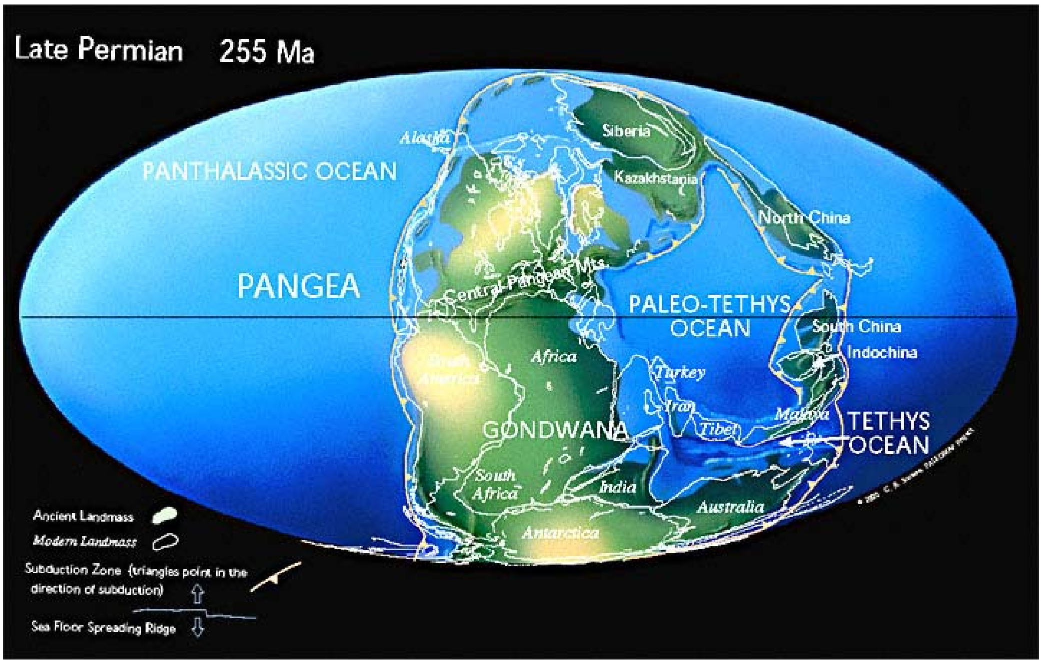
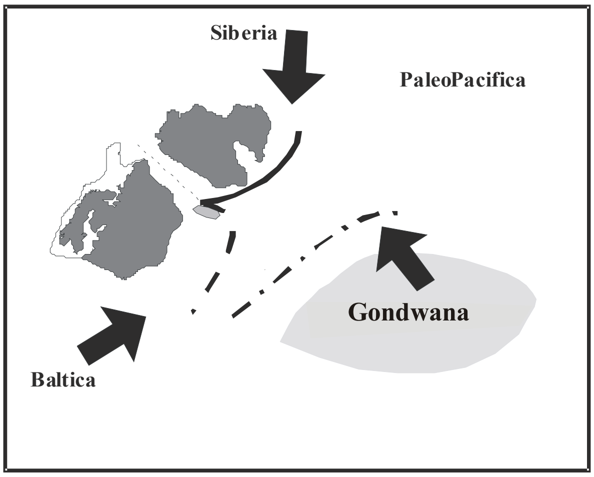


Figure 4.12. Global reconstruction for the Late Permian (http://www.scotese.com).



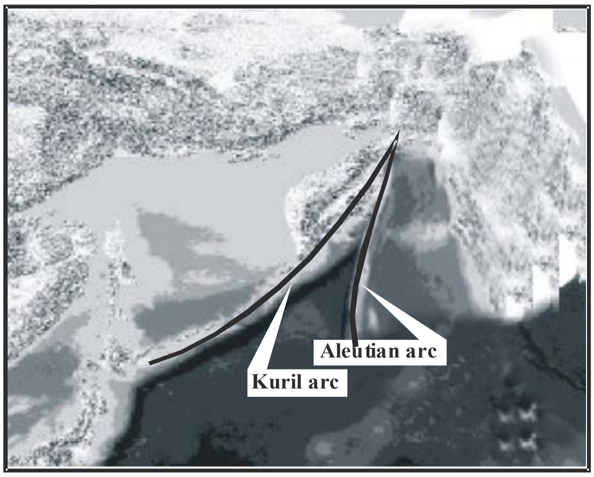


Figure 4.13. Triple junction model for the evolution of Kazakhstan (Permian) and possible line of evolution for the Circum Pacific region.

Close to Permian time Kazakhstan's structures have got a present day looking pattern. And since Permian time a history another tectonic epoch began.

Conclusion: the suggested model of Paleozoic tectonic evolution is able to explain an origin of bent orogenic belts still in the frames of classic conception plate tectonic theory.

Part 5. Conclusion

Despite significant progress during the last decade, the overwhelming majority of the details of the crustal evolution of Kazakhstan still remain enigmatic. The central question whether Kazakhstan amalgamated during the Ordovician and acted as a coherent microplate since or whether Kazakhstan is the result of continuous accretion of terranes and arcs along a major subduction system throughout the Paleozoic is still unanswered. Defining structural units and reconstructing their interaction relative to each other and with respect to Siberia and Baltica will improve our understanding of continent formation in Central Asia. Addressing this problem, a detailed paleomagnetic study of Kazakhstan was undertaken.

Between 2002 and 2004, three field trips to Kazakhstan have been carried out and more than 1100 samples have been studied in the paleomagnetic laboratory of the Geophysics Section of the Department for Earth and Environmental Sciences, Ludwig-Maximilians Universiät, München.

1. Prefolding magnetizations have been obtained for 4 localities (table 5.1) and postfolding magnetizations have been obtained for 10 localities (table 5.2).

Table 5.1. Prefolding directions of magnetization.

Age of rocks	Loc. Lat. [°N]	Loc. Long. [°E]	D [°]	I [°]	α95 [°]	Pol. Lat [°]	Pol. Long [°]	dp/dm [°]	φ [°]	Age of magnetiza-tion
S-D_1	43°48’	75°28’	346.9	23.8	12.4	56.7	279.3	7.1/13.4	12.4 +7.7/-6.6	S-D_1
O_1	43°02’	74°54’	9.2	-16.9	15.0	37.7	243.3	8.0/15.5	-8.6 –8.7/+7.6	O_1-O_3
D_3-C_1	43°15’	74°50’	69.5	43.7	9.5	31.7	158.2	7.4/11.9	25.5 +8.3/-6.7	C_1-T
D_1	43°54’	75°32’	348.5	73.6	7.0	72.9	55.4	11.3/12.6	59.5 +12.2/-10.4	D_1-D_2

Loc. Lat. and Loc. Long – the locality position; D - declination; I - inclination; α95 - radius of confidence circle. Pol. Lat, Pol. Long and dp/dn are the latitude, longitude, and radius of 95% confidence circle of the paleopole, respectively; φ - paleolatitude.

Table 5.2. Postfolding directions of magnetization

Age of rocks	Loc. Lat. [°N]	Loc. Long. [°E]	D [°]	I [°]	α95 [°]	Pol. Lat [°]	Pol. Long [°]	dp/dn [°]	φ [°]	Age of magnetiza-tion
S-D1	43°48’	75°28’	355.5	35.6	9.6	65.6	265.8	6.4/11.1	19.7 +7.3/-6	post D2
O2	43°10’	74°53’	215.7	-51.3	5.9	59.8	174.6	5.4/8.0	32.0 +5.8/-5.1	post O3
O1	43°02’	74°54’	249.7	-57.3	5.1	38.3	145.3	5.4/7.4	37.9 +5.8/-5.1	post O3
C1	45°59’	73°34’	17.0	63.4	10.8	78.1	162.4	13.5/17.1	45.0 +20.5/-11,8	post C1
D3-C1	43°22’	75°08’	10.4	38.6	7.2	66.7	230.0	5.1/8.6	21.8 +5.4/-4.8	post C1
D1-D2	44°21’	73°51’	33.1	66.6	11.5	67.0	139.9	15.6/18.9	49.1 +18/-13.5	post D2
D1	43°54’	75°32’	10.4	54.8	26.8	78.3	209	26.8/37.9	35.3 +38.2/-20.4	post D2
S-D_1	51°18’	74°19’	332.8	85.1	6.7	59.7	65.5	13.3/13.1	80.3 +9.7/-12.6	post D_2
S-D_1	49°35’	76°56’	200.0	-65.2	15.5	56.7	279.3	25.1/20.3	47.3 +24.6/-16.8	post D_2
D_3	49°03’	67°49’	10.9	62.3	6.9	80.7	189.4	10.7/8.4	43.6 +9.2/-7.7	post C_2

2. The results of the research described in this thesis can be summarized as such:

a) Since the Middle Ordovician, North and South Kazakhstan show no significant difference in latitudinal positions.

b) The majority of the paleomagnetic data indicate that in the Palaeozoic, both South and North Kazakhstan were situated slightly further to the North than it would be expected if Kazakhstan was a part of Baltica, or slightly further to the South than it would be expected if Kazakhstan was a part of Siberia. Since the Ordovician up to the Permian Kazakhstan (including all it’s parts) moved from Southern latitudes into northern latitudes with drift rates close to those of Baltica and Siberia;

c) Kazahkstan was affected by several remagnetization events of significant regional extent. Permian remagnetization, widespread in Baltica, only played a minor role.

3. Existing tectonic models have been tested using reliable paleomagnetic data obtained during the last five years. As a result it is postulated that paleomagnetic data cannot be reconciled with tectonic models such as the one for the evolution of the Kipchak arc [Sengör and Natal’in, 1996].

4. The APWP of Kazakhstan has been reviewed using modern paleomagnetic results.

5. Contradict a hypothesis of the orocline bending [Sengör and Natal'in, 1996], a model was suggested, which is able to explain the bent structures of Kazakhstan within the classic conception of plate tectonic.

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