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Late Cretaceous–Cenozoic deformation of northeast Asia

C. Gaina [a,*], W.R. Roest [b], R.D. Müller [a]

[a] School of Geosciences, University of Sydney, Sydney, NSW 2006, Australia
[b] Department of Natural Resources Canada, Geological Survey of Canada, Ottawa, ON, Canada K1A 0E9

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Abstract

The plate tectonic paradigm implies rigid plates and narrow plate boundaries. In contrast, diffuse plate boundaries are common both in the oceans and continents [R.G. Gordon, Annu. Rev. Earth Planet. Sci. 26 (1998) 615–642], and their history is difficult to constrain, especially in remote, tectonically complex areas such as northeast Asia [M.E. Chapman, S.C. Solomon, J. Geophys. Res. 81 (1976) 921–930]. Here we show how extensive North Atlantic marine magnetic [R. Macnab et al., EOS 76 (1995) 449, 458] and gravity data [D.T. Sandwell, W.H.F. Smith, J. Geophys. Res. 102 (1997) 10039–10054] can be used to unravel, with tight confidence limits, successive periods of deformation over 80 million years, along the diffuse continental Eurasian–North American plate boundary. A period of compression in the Late Cretaceous (14 mm/yr in the Laptev Sea to 20 mm/yr in Kamchatka) led to thrusting in the Verkhoyansk Mountains, and was followed by extension from 68 to 40 Ma when ~400 km of extension was accommodated by the formation of a series of grabens, including the Moma Rift system. Since 40 Ma, time-varying compression and transpression along the Moma Rift system created strike-slip faults, thrusts and folds at rates up to 6.3 mm/yr. In the Laptev Sea region, 600 km of extension from latest Late Cretaceous to present created the Laptev Sea and Lena Rift systems. The deformation predicted by our model fits most geological features formed in the Laptev Sea and central northeast Asia during Late Cretaceous–Cenozoic times. The most recent deformation (Late Miocene–Pliocene) is not very well constrained since our model lacks data younger than 11 Ma. The deformation that occurred in Kamchatka reflects a complex tectonic setting and our model's predictions are only tentative.

Keywords: plate boundaries; northeast Asia; magnetization; rotation; pole positions; compression; extension; strike-slip faults

1. Introduction

Northeast Asia owes much of its structural complexity to its setting close to the diffuse plate boundary between the North American and Eurasia plates and close to the Euler rotation pole for their relative motion. Previous models for the opening of the North Atlantic [5–9] result in very diverse North American–Eurasian stage rotations through time, inferring compression, strike-slip or extension for the same area. For example Srivastava and Tapscott's [7] model, which used data along the entire boundary between Eurasia and North America for the first time, predicts compression prior to chron 13

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* Corresponding author.
E-mail address: carmen@es.usyd.edu.au (C. Gaina).

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(33.1 Ma; we use Cande and Kent [10] throughout this paper), followed by strike-slip until present. Lawver et al. [9] present a series of tectonic reconstructions for the last 180 Ma in the Arctic Ocean, based on a compiled set of rotations and predict transtension and extension in the Laptev Sea region from 40 Ma onward, but they do not discuss the implications of their model for northeast Asia.

The present location of the North America–Eurasia plate boundary in northeast Asia is defined by a belt of earthquakes from the Laptev Sea to the Cherskii Mountains, until it meets the Okhotsk plate at a triple junction southeast of the Cherskii Mountains [11] (Fig. 1). Gordon [1] included this region among other diffuse plate boundaries that were determined based on seismicity, topography, evidence of faulting and nonclosure of plate motion circuits. The Gakkel Ridge in the Eurasian basin (Fig. 2) appears to continue landward into a series of extensional features through the Laptev Sea and Cherskii Mountains [2,11–13]. However, recent earthquake focal mechanism solutions indicate that south of the Laptev Sea the plate boundary is subject to strike-slip and compression [11,13]. Avetisov [14] suggested that the Gakkel Ridge continuation through the Laptev Sea has two seismically active branches, isolating a Laptev Sea microplate, but Drachev [15] shows, based on seismic reflection data, that the plate boundary migrated from west to the east and is now established along the central Laptev Sea. The plate boundary has been suggested to continue to the southeast along

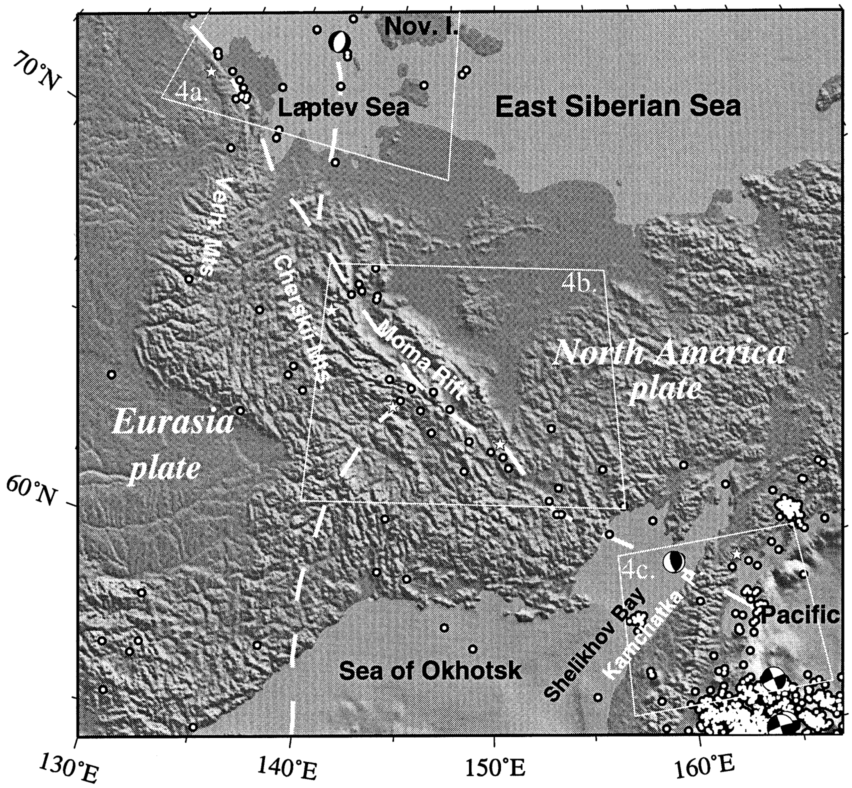

Fig. 1. Digital terrain elevation of northeast Asia (GTOPO-30, USGS Eros Data center). Present day seismicity (National Earthquake Information Center, World data Center for Seismology, Denver, USA) is represented by white circles; also shown are mechanisms for earthquakes with magnitudes larger than 5. The generalized locations of present day plate boundaries are indicated by the dashed white lines. The regions in the inset boxes are shown in Fig. 4. White stars show starting points for modelled motion vectors also displayed in Fig. 4.

the Moma Rift graben system [12], but Fujita [13], and Imaev et al. [16], based on present day seismicity, argue that the graben system has been abandoned in recent times. Southeast of the Cherskii Range and Moma Rift the present plate boundary geometry indicates a triple junction between the North America, Eurasia and the Okhotsk plates (Fig. 1). Riegel et al. [17] show that this junction cannot be located very accurately, and the time of its inception and geometry has been a matter of debate [2,11]. The Sea of Okhotsk plate was accreted to the Eurasian plate in the Late Cretaceous–Early Paleocene, after subduction of the Kula plate terminated [18]. Other studies indicate that compression or strike-slip motion continued between the Okhotsk and neighboring plates until Eocene [19] or started in Oligocene after a period of quiescence [20,21]. A series of young strike-slip faults indicate that about 3 million years ago the Okhotsk plate became an independent plate [11,17], and present day seismicity indicates it still is today.

This study presents the first quantitative approach, i.e. including a treatment of the uncertainties, to the prediction of plate tectonic motions in northeast Asia. Using a very large magnetic and fracture zone database for the North Atlantic and Arctic oceanic region, we resolve the relative motion between North America and Eurasia since Late Cretaceous. The ocean-based results are then extended on land and analyzed in the light of the large-scale tectonic history and the geology of northeast Asia.

2. New tectonic model for the opening of North Atlantic and Arctic oceans

An extensive magnetic database [3] (Fig. 2) and morphological data derived from satellite gravity anomalies [4] were used to construct a new plate tectonic model for the opening of the North Atlantic Ocean. The relative motion between North America and Eurasia from chron 33 (79 Ma) to chron 25 (55.9 Ma) was constrained by magnetic and fracture zone data between the southern Rockall Plateau and King's Trough (Fig. 2). The North-America, Eurasia and Greenland plates constituted a three-plate system between chrons 24 (53.3 Ma) and 13 (33.06 Ma). Following Srivastava and Tapscott [7], we assumed that the Lomonosov Ridge was attached to North America during the opening of the Eurasian Basin. Magnetic anomalies 33 (79 Ma) to 5 (11 Ma) were identified in a consistent fashion (choosing the old end of the normal polarity interval, with the exception of chrons 13 and 25 where the young end is more characteristic) and digitized throughout the entire area (Fig. 2). They were inverted together with fracture zone crossings (Fig. 2) based on gridded gravity data [4]. For the two-plate case, we used Royer and Chang's [22] method, whereas Kirkwood's [23] method was used for triple junction closure. We assigned a 1σ uncertainty of 5 km to both magnetic and fracture zone data, based on previous studies [24–26], which showed that this is an acceptable median value for marine geophysical data. The parameter $\hat{\kappa}$ indicates whether the assigned uncertainties are correct ($\hat{\kappa} \approx 1$), underestimated ($\hat{\kappa} \ll 1$) or overestimated ($\hat{\kappa} \gg 1$). According to the values of $\hat{\kappa}$ from Table 1a, the assigned uncertainties are very close to true uncertainties in most cases, except for chrons 5 and 18, for which data uncertainties are slightly overestimated, and for chron 21 data points, whose uncertainties we underestimated.

We present locations of anomaly picks used in this study (white symbols) along with their restored positions (black symbols), both for the eastern and western (conjugate) flanks of the North Atlantic, Labrador Sea and Arctic Basin (Fig. 2). The inversion derives a best-fit reconstruction pole by minimizing the misfit between conjugate isochrons. Generally, the present position of anomaly picks and the reconstructed picks from the conjugate side agree well (Fig. 2). For the two-plate case we were able to use normal quantile plot (qq-plot) and histograms of data residuals to test the normality of the data distribution and the distribution of normalized residuals between best-fitting great circle segments and magnetic anomaly and fracture zone data (Fig. 3). If the data residuals are normally distributed, all points in the plot should lie on a straight line. Most reconstructions are characterized by an ap-

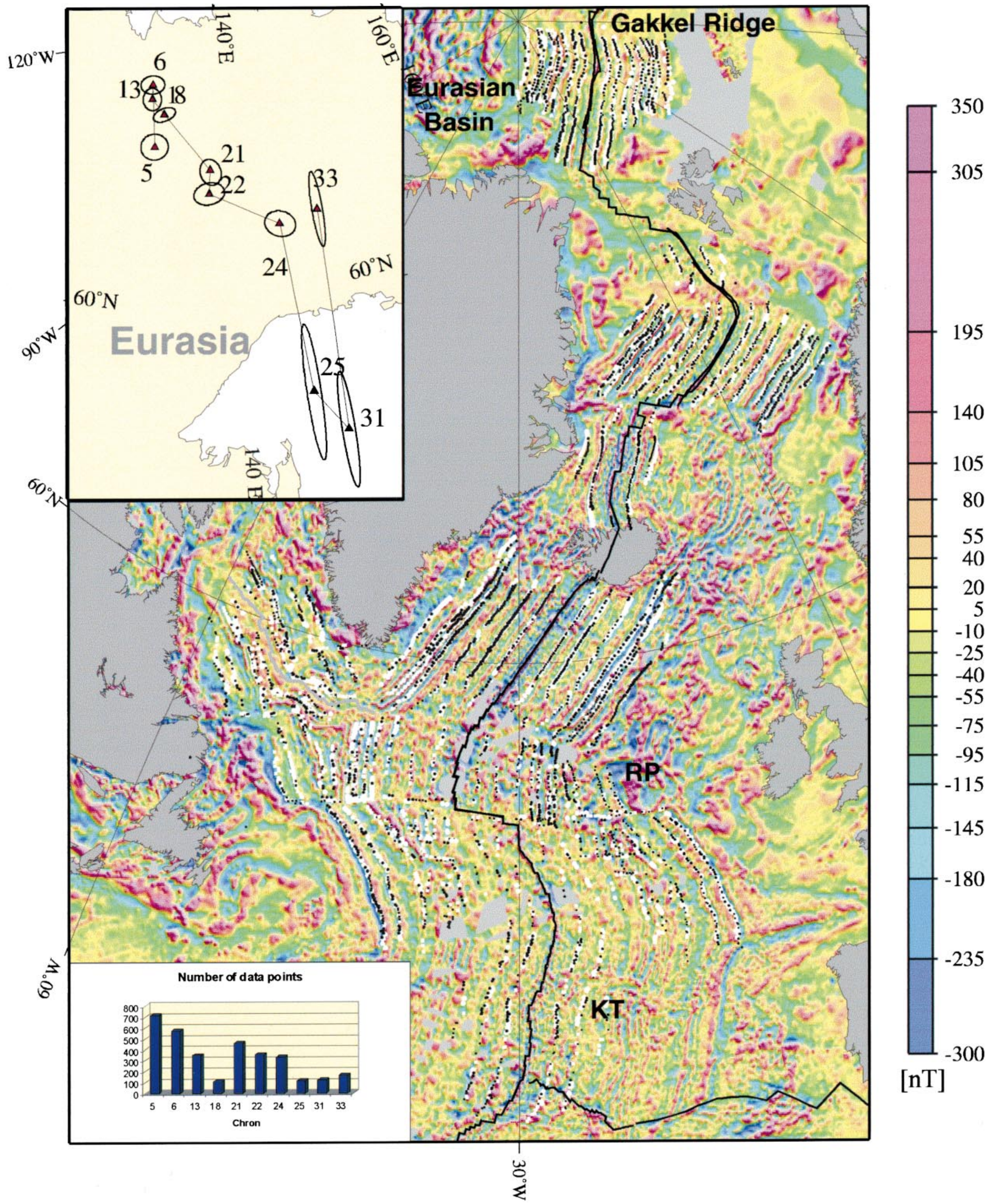
Gakkel Ridge
Eurasian Basin
RP
KT
120°W
90°W
60°N
60°W
30°W
140°E
160°E
60°N
60°N
Eurasia
140 E
6
13
18
5
21
22
33
24
25
31
Number of data points
800
700
600
500
400
300
200
100
0
5
6
13
18
21
22
24
25
31
33
Chron
350
305
195
140
105
80
55
40
20
5
-10
-25
-40
-55
-75
-95
-115
-145
-180
-235
-300
[nT]

Fig. 2. Gridded magnetic anomalies in the North Atlantic region [3] (white areas contain no data). Superimposed are interpreted magnetic anomaly crossings (white symbols) and rotated magnetic anomaly picks (black symbols). Present day plate boundaries are thin, black lines. RP stands for Rockall Plateau and KT is King's Trough. The number of data points used for inversion as well as the locations of finite rotation poles for North America–Eurasia (red triangles) with their 95% uncertainty ellipses are shown in the inset maps.
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proximately linear distribution in qq-plots. Only the histogram for chron 25 deviates substantially from a Gaussian distribution, which we largely attribute to the small number of data points for this isochron.

The new finite rotation poles, that describe the relative motion between the North America and Eurasia plates (Tables 1a, b), are displayed in the inset figure in Fig. 2, together with their 95% confidence regions. A comparison with previous finite rotation poles from several selected studies is given in Table 2. In general, the differences among the finite rotation poles for all models are not very large. However, small differences in finite rotation poles may lead to significant variations in stage rotations and predicted relative motions. None of the previous studies included a comprehensive error analysis that demonstrates how finite rotation uncertainties influence those predictions. A more detailed discussion of our model and quantitative tectonic reconstructions for the Labrador and Norwegian Greenland seas will be presented elsewhere.

3. Northeast Asia crustal deformations

Our new plate tectonic model (Tables 1a and b), based on the seafloor spreading history of the Arctic and North Atlantic oceans, was used to compute vectors, and their uncertainties, for the relative motion between North America and Eurasia in northeast Asia. In Fig. 4a–c, this displacement through time is represented by the successive motion of several points attached to the Eurasian plate for 10 stages, from chron 33 (79 Ma) to the present. For each stage rotation vector, a simultaneous confidence region (that represents the area in which a point on a given plate may have been located with equal likelihood for a particular reconstruction time, with 95% confidence) is plotted at the young end of the relative motion vectors.

In the Laptev Sea, at 72°N and 122°E, this model predicts 209 ± 2 km of compression between chron 33 (79 Ma) and 31 (68.7 Ma), followed by extension and transtension (452 ± 20 km) until the Middle Eocene, and extension (186 ± 28 km) until the present (Fig. 4a). The Lap-

Table 1a
Finite rotations for North America–Eurasia (Eurasia fixed)

Chron	Age Ma	Latitude +°N	Longitude +°E	Angle °	r	$\hat{\kappa}$	dF	N	s
5o	10.95	66.44	132.98	2.57	340.872	1.90	649	714	31
6o	20.13	68.91	132.59	5.09	465.969	1.11	519	574	26
13y	33.06	68.22	131.53	7.65	180.061	1.56	281	346	31
18o	39.5	67.72	133.91	9.25	33.684	2.52	85	106	9
21o	47.91	65.38	138.44	10.96	537.712	0.74	400	460	27
22o	49.71	64.52	138.18	11.50	288.623	1.06	305	353	21
24o	53.34	63.07	144.26	12.82	340.229	0.84	285	329	19
25y	55.9	56.17	145.06	13.24	109.063	0.89	97	112	6
31y	68.73	54.45	147.06	15.86	98.628	1.04	103	120	7
33o	79.08	63.40	147.75	18.48	136.429	1.00	137	158	9

Parameters: r, misfit; $\hat{\kappa}$, estimated quality factor; dF, degrees of freedom; N, number of data points; s, number of great circle segments; the uncertainty of fracture zone and magnetic anomaly identifications is $\sigma = 5.00$ km; ages are after the *Cande and Kent* [10] timescale.

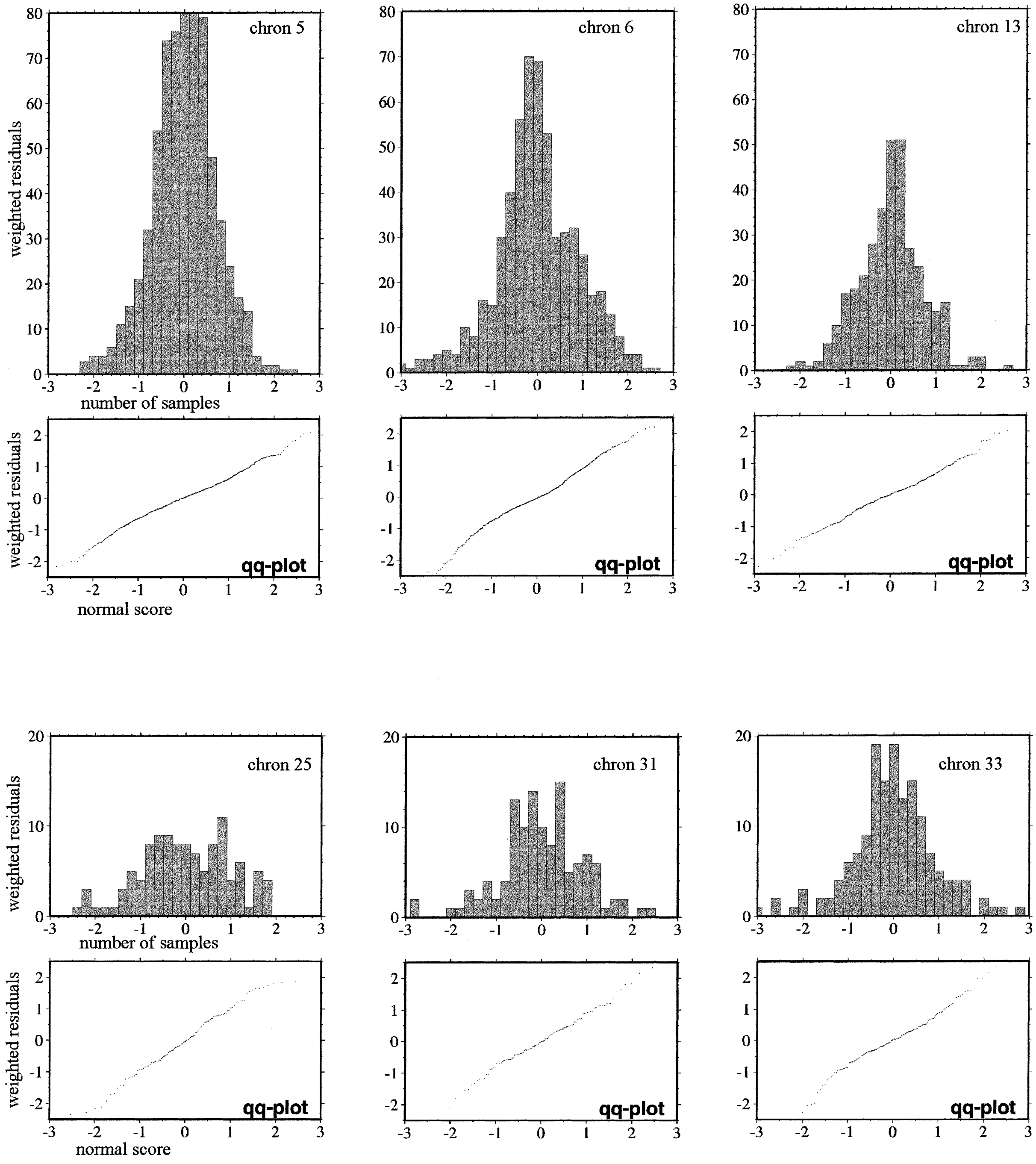

Fig. 3. Qq-plots and histograms of the weighted residuals for reconstructions based on a two-plate system. The histograms of data residuals show the distribution of the normalized residuals between best-fitting great circle segments and magnetic anomaly and fracture zone data. The Gaussian distribution of weighted residuals and the linear distribution in qq-plots indicate a good match between magnetic anomaly and fracture zone picks from one flank and their rotated counterparts. Due to a slightly smaller amount of data points used for the chron 25 reconstruction, the histogram deviates from a Gaussian distribution.

tev Sea is bordered both on the eastern and western side by folded complexes that formed in the Late Cretaceous, and are considered as the offshore branch of the Verkhoyansk fold belt [15,27]. There are numerous NW–SE oriented grabens in the Laptev Sea that are filled with Late Cretaceous–Cenozoic sediments [28,29] reflecting an extensional regime. Drachev [15] identified several stratigraphic unconformities (Early Eocene, Early Oligocene, and Middle Miocene) that coincide with changes in the direction of relative plate motion between North America and Eurasia at chrons 24, 13 and 5 (53 Ma, 33 Ma, and 11 Ma, respectively), in accordance with our model. Paleocene grabens are described by Drachev [15] south of the Laptev Sea (Yana-Indigirka Lowland and Lena Delta), in agreement with modelled extension during this time. A period of transpression from Oligocene to Middle Miocene suggested by Drachev [15] based on seismic data is predicted by our model only for the southern part of the Laptev Sea for Early to Middle Miocene (9 ± 3 km at 69°N and 130°E).

Further south, in the Verkhoyansk Mountains region, our model predicts a compressional regime for the Late Cretaceous that led to the development of frontal thrusts [30]. According to Parfenov [31], folding of the Verkhoyansk thrust front was initiated during sedimentation as early as in the Late Jurassic due to collision with the Kolyma–Omolon superterrane. The opening of the Atlantic Ocean in the Late Jurassic was synchronous with the beginning of the convergent regime that triggered terrane accretion along the borders of the Eurasian and North American cratons. By the end of the Late Cretaceous this amalgamation was in its final stage. A conjugate set of NE and NW striking faults that displace Verkhoyansk fold axes and thrusts are described by Parfenov [31], who concluded that they express the latest stage of deformation in the latest Cretaceous. The consistent orientation of the faults throughout this sector indicates a uniform tectonic stress field due to transpression in a nearly east–west direction [32] and this is in agreement with our prediction (Fig. 4b). Parfenov [30] estimated about 150–200 km of compression between the two plates, whereas our model predicts 248 ± 2 km of transpression from chron 33 (79 Ma) to chron 31 (68.7 Ma) at 67°N and 140°E. The transtensional/extensional regime that started afterwards changed to compression since chron 13 (33 Ma, Oligocene) and is expressed in some thrusts and dislocations in the northern Verkhoyansk Mountains [28,33].

In central northeast Asia (64°N and 143°E), our model implies transtension (420 ± 15 km) from chron 31 (68.7 Ma) to chron 18 (39.5 Ma) (Fig. 4b), which subsequently changed to transpression/compression (97 ± 13 km). Although the

Table 1b
Eurasia–North America rotation covariances

Chron	a $(\times 10^{-8}$ rad$^2)$	b	c	d	e	f
5o	3.03	1.53	1.43	2.78	−1.98	7.00
6o	5.15	2.95	7.95	4.03	−3.10	9.23
13y	8.32	1.65	5.50	5.90	−9.14	32.8
18o	19.20	21.53	3.91	39.07	−9.68	37.21
21o	9.21	2.06	8.78	8.94	−5.30	27.51
22o	17.54	14.87	9.19	27.89	−4.33	31.74
24o	16.35	11.03	20.44	28.88	5.68	46.74
25y	326.57	−311.14	519.56	321.60	−502.81	840.31
31y	380.47	−377.25	605.52	409.53	−607.59	975.24
33o	234.65	−240.10	383.59	279.58	−399.17	635.98

The covariance matrix describes uncertainties in the finite rotations and is computed as following:

$$\begin{pmatrix} a & b & c \\ b & d & e \\ c & e & f \end{pmatrix}$$

Cretaceous period was mainly characterized by a compressional regime, it seems that toward the end of this period compression was gradually replaced by extension. This fact is outlined by studies on the Cretaceous thrusting in the Verkhoyansk fold belt [31] that state that deformation ended by the Late Cretaceous. Several authors described the Moma Rift system as a series of grabens scattered along the Cherskii Mountains with a range of ages from Paleocene to Neogene [12,33]. Although this name has been used more restrictively (only for the graben along the Moma River [34]) we will use 'Moma Rift' to refer to the entire rift system. The Paleocene to Eocene transtensional period predicted by our model accounts for the formation of the Moma Rift graben system (about 75 km wide) and its southward decrease in both depth and width [12]. The transpressional regime that started in the Late Eocene is likely to have formed the structures described by Kosygin and Parfenov [35] as a system of strike-slip, reverse faults and thrusts visible on the magnetic anomaly map as NW–SE linear highs and troughs (Fig. 4b). Folding southeast of the Moma Rift provides additional evidence for Cenozoic compressional deformation in central northeast Asia [33]. The strike-slip faults that cross the Moma Rift grabens and displace them [27] were also likely formed under this compressional regime. This interpretation confirms Cook et al.'s [11] suggestion that the faults used by Savostin and Karasik [36] to determine the present day rotation pole of North America–Eurasia represent past plate motions. Since the Moma Rift system is not presently seismically active, it has been suggested that the plate boundary migrated toward the southwest where seismicity and high heat flow values indicate a tectonically active zone [37]. Focal mechanisms of earthquakes in this area show strike-slip motion [13] and its orientation is in agreement with the strike-slip motion implied by our model since chron 5 (11 Ma). Imaev et al. [16] described a series of small pull-apart basins bounded by en-echelon strike-slip faults, close to the larger basins of the Moma Rift system. These likely reflect the recent transpressional regime. The location of our stage pole for chron 5 (11 Ma) to present cannot predict the recent tectonic regime that might have changed about 3 Myr ago (and therefore cannot explain the Pliocene deformations from the Moma Rift).

As discussed previously, the timing of the Okhotsk plate collision and its subsequent motion relative to the Eurasian and North American plates is still controversial. Since the Okhotsk plate might have again become a separate entity in the last 5 million years or less [17], the extrapolation from chron 5 (11 Ma) to present gives only a rough estimation of the tectonic regime.

Table 2
Finite rotations for North America–Eurasia (Eurasia fixed) from selected previous studies

Chron	Latitude +°N	Longitude +°E	Angle °	Reference
5	68.0	137.0	2.50	(a)
	68.0	137.0	2.50	(b)
	64.64	136.93	2.29	(c)
	66.44	132.98	2.57	(d)
6	–	–	–	(a)
	68.0	138.20	4.75	(b)
	67.99	130.22	4.57	(c)
	68.91	132.59	5.09	(d)
13	65.0	133.0	7.60	(a)
	68.0	129.90	7.78	(b)
	68.76	136.01	7.69	(c)
	68.22	131.53	7.65	(d)
21	56.0	144.0	9.90	(a)
	67.12	137.28	10.94	(b)
	65.65	139.16	10.52	(c)
	65.38	138.44	10.96	(d)
24	–	–	–	(a)
	62.28	140.37	12.68	(b)
	62.42	141.02	12.52	(c)
	63.07	144.26	12.82	(d)
25	63.0	157.0	14.37	(a)
	63.25	143.89	14.15	(b)
	64.17	143.27	14.08	(c)
	56.17	145.06	13.24	(d)
31	77.0	130.0	21.16	(a)
	70.66	145.91	17.59	(b)
	–	–	–	(c)
	54.45	147.06	15.86	(d)
33	–	–	–	(a)
	74.52	147.69	20.30	(b)
	–	–	–	(c)
	63.40	147.75	18.48	(d)

(a) Pitman and Talwani, 1972 [5], (b) Srivastava and Tapscott, 1986 [7], (c) Rowley and Lottes, 1988 [8], and (d) this study.

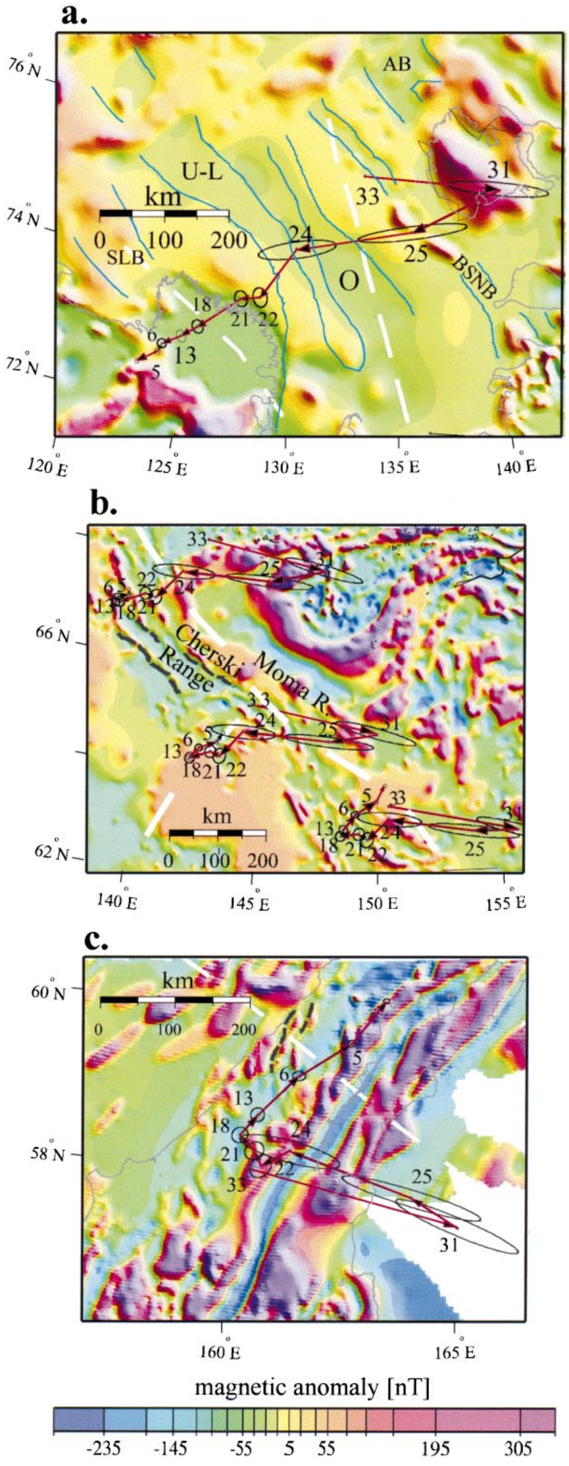

Fig. 4. Relative motion between Eurasia and North America since the Late Cretaceous in (a) the Laptev Sea, (b) central northeast Asia, and (c) the Kamchatka Peninsula illustrated by motion vectors and their 95% uncertainty regions for 10 stages (North America plate fixed), superimposed on magnetic anomalies (U.S. National Geophysical Data Center). In the Laptev Sea the main grabens are from east to west: South Laptev Basin (SLB), Ust–Lena (U–L) (50–70 km), Omoloi (O), Bel'kov–Svyatoi Nos (BSNB) (50 km) and Anisin (AB) (20–35 km). The dashed gray lines on (b) and (c) outline NW–SE trending magnetic lineations. Coastlines are in light gray, and the present day plate boundaries in dashed white lines.
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Therefore, the amount of motion that our model predicts for different locations east of the present day triple junction does not necessarily relate directly to the observed geology.

The northern Kamchatka Peninsula (60°N and 163°E) was characterized by 73 ± 4 km of dextral strike-slip between chrons 31 (68.7 Ma) and 25 (55.9 Ma), 174 ± 4 km of transtension between chrons 25 (55.9 Ma) and 24 (53.3 Ma), and 43 ± 4 km of extension between chron 24 and 22 (48.6 Ma). After a small amount of transpression and strike-slip (51 ± 6 km), the Kamchatka Peninsula was subjected to 264 ± 7.5 km of compression from chron 18 (39.5 Ma) to present (Fig. 4c). Even though most of Kamchatka Peninsula geology reflects the interactions between Pacific, Kula, and North America plates, there are several structural features, whose orientation reflects North America–Eurasia relative plate motions. For example, Savostin [36] described an EW oriented trough as a continuation of the Moma Rift system in northern Kamchatka, and the compressional event that started about 40 Ma ago may have produced the NW–SE thrust faults in NE Kamchatka Peninsula also visible on the magnetic map (Fig. 4c). This regime continues in the present, although this reflects rather the relative motion between the North America and Okhotsk plates [38].

4. North America–Eurasia – a diffuse plate boundary

The tectonic regimes and the amount of motion predicted by our model for a broad region in northeast Asia is summarized in Fig. 5. The generalized location of the present day plate boundary (based on previous studies and present day seismicity) is used for all time slices as a guide. It is important to point out, though, that the north Asian craton (i.e. Siberia and Verhkoyank mountains) had only subtle changes in paleolatitude for the last 100 million years [19], making this a reasonable frame of reference. The migration of the stage pole to a location close to the plate boundary triggered a complex tectonic regime that varied from extension to strike-slip and compression along a broader area from the Laptev Sea to northern Kamchatka.

Starting in the Middle Eocene, the North America–Eurasia stage pole divided the boundary between the two plates in two major regions subjected to either extension or compression, linked by a smaller area closer to the pole that experienced strike-slip motion. According to Gordon [1] diffuse plate boundaries are located in the proximity of rotation poles, and relative plate motions vary in speed from ~2 to ~16 mm/yr. Gordon [39] named the pole of rotation that lies between paired convergent and divergent zones 'convergent–divergent pivot'. Therefore, the plate boundary between North America and Eurasia plates in northeast Asia has changed from a distinct to diffuse state at about 40 Ma ago. This coincides with a major tectonic event south of Eurasia, in the Tethys Ocean, that might have triggered northward acceleration of the Australian plate and cessation of seafloor spreading in the Wharton Basin, leading to the amalgamation of the Indian and Australian plate into a single Indo-Australian plate [40].

GPS data [41] indicate that, recently, the North America–Eurasia stage pole may have moved close to the Laptev Sea. This is also supported by stress vectors [42] indicating compression south of the Lena Rift system, in contradiction with the strike-slip motion predicted by our model (Fig. 5h), which depicts the average motion over the last 11 Ma. The timing of the onset of this most recent compressional regime is not known. It appears to co-exist with a transcurrent regime since the majority of faults described in the Cherskii Mountains indicate strike-slip motion [16].

In an analysis of a continental deforming zone, England and Molnar [43] showed that the width-to-length ratios of actively deforming regions are consistent with deformation determined by the creep of the lower lithosphere rather than by brittle deformation. England and Molnar [43] chose three plate boundaries subjected to transcurrent deformation (the Pacific–North America plate boundary zone in California, South Island of New Zealand and Pacific northwest of North America) and, using Sonder et al.'s [44] relationship:

$$w \approx L/\pi\sqrt{n}$$

(where w is the width of deformed region, L is the plate boundary length, and n is the exponent of the effective power law and represents the vertical averaging of deformation involving slip on faults), they derived a value of $n = 3$–4.5. As stated by Sonder et al. [44] a value of $n < 10$ indicates that deformation is controlled by the lower lithosphere, whereas values of $n > 10$ show that a substantial fraction of strength may be supported by friction on faults.

Considering the spatial variation along the modern plate boundary between North America and Eurasia, we divided it into two branches: one in the Laptev Sea and the other from the southern Laptev Sea along the Cherskii Mountains. In order to analyze the vertically averaged rheology of

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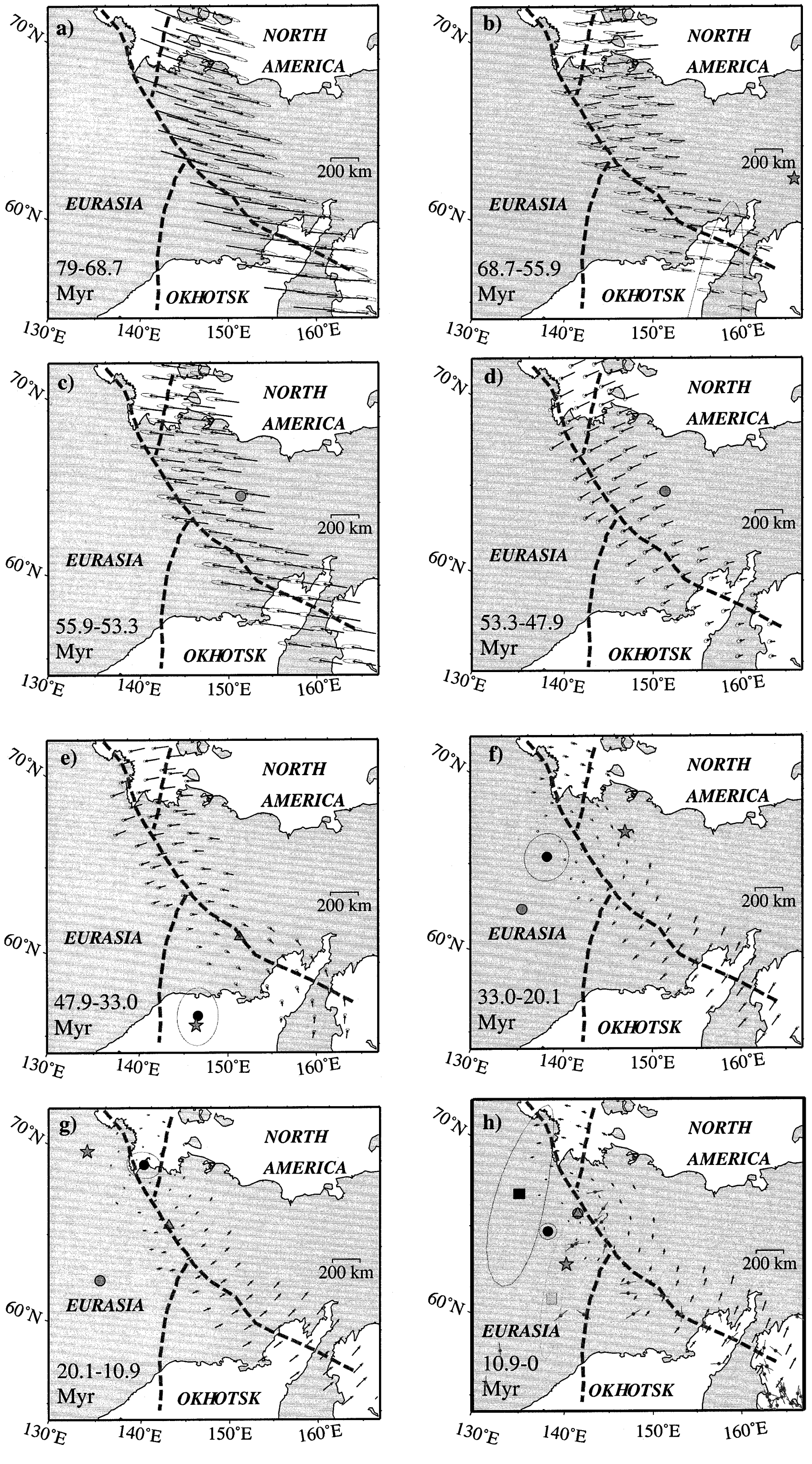
Fig. 5. (a–h) Motion vectors and their 95% uncertainty regions for eight stages plotted along the plate boundary between North America and Eurasia (Eurasia plate is fixed). We used as a guide the present day plate boundaries. Stage poles are black filled circles, previously determined stage poles are shown for comparison (gray circles (Pitman and Talwani, 1972), gray triangles (Srivastava and Tapscott, 1986), and stars (Rowley and Lottes, 1988)). For the youngest stage the pole derived from GPS measurements (filled square (Larson et al., 1997)), the NUVEL-1A pole (gray square (DeMets et al., 1990)) and stress vectors (gray bars and circles) from World Stress Map (Zoback, 1992) are also shown.


a)
NORTH AMERICA
EURASIA
OKHOTSK
200 km
79-68.7 Myr
b)
NORTH AMERICA
EURASIA
OKHOTSK
200 km
68.7-55.9 Myr
c)
NORTH AMERICA
EURASIA
OKHOTSK
200 km
55.9-53.3 Myr
d)
NORTH AMERICA
EURASIA
OKHOTSK
200 km
53.3-47.9 Myr
e)
NORTH AMERICA
EURASIA
OKHOTSK
200 km
47.9-33.0 Myr
f)
NORTH AMERICA
EURASIA
OKHOTSK
200 km
33.0-20.1 Myr
g)
NORTH AMERICA
EURASIA
OKHOTSK
200 km
20.1-10.9 Myr
h)
NORTH AMERICA
EURASIA
OKHOTSK
200 km
10.9-0 Myr
70°N
60°N
130°E
140°E
150°E
160°E

the lithosphere along this diffuse plate boundary, we estimated the lengths and widths of the two plate boundary branches from published maps of seismicity and fault locations [15,16,45]. South of the Laptev Sea, along the Cherskii Mountains, we estimate that a region 2000 km long and 400 km wide [45] is subjected mainly to strike-slip, and we obtained a value of $n \simeq 2.54$. This value confirms England and Molnar's [43] results and suggests that deformation along the diffuse boundary in continental northeast Asia is controlled by the lower lithosphere.

For the case of extension or compression England and Molnar [43] showed that

$$w \approx 4L/\pi\sqrt{n}$$

Using this expression in the Laptev Sea, with a plate boundary length of 600 km and a width of 200 km, we computed $n \simeq 15$ (the plate boundary dimensions were chosen for the active central branch, through Omoloi and Ust–Lena grabens, ignoring the weaker Lena–Tamyr branch). A similar result has been obtained by Gordon [39] for the continental diffuse plate boundary between Nubia and Somalia. Based on the depth of earthquake occurrence (25–30 km), he concluded that this area has a relatively thick brittle lithosphere, which controls the geometry of the deforming zone. The same situation appears to hold for the Laptev Sea, whose relatively wide zone of deformation and large value for n resembles those of the East Africa Rift. As shown by Jemsek et al. [46] and Fujita et al. [13] Laptev Sea earthquakes also occur at depths greater than 15 km. The consistency of these observations may indicate that in these actively extending areas the strength of the mantle lithosphere has deteriorated more quickly than that of the crust.

From the above, we conclude that diffuse continental plate boundaries are subjected to more complex deformation processes, with crustal deformation significantly different from that in the mantle lithosphere. Therefore, it is hard to infer successions of kinematic events based only on the regional geology. We suggest that in this case, other constraints (like marine geophysical data) from the narrow, oceanic segment of the plate boundary could be used to deconvolve the tectonic history of the continental plate boundary.

5. Conclusions

A new model for the opening of the North Atlantic and Eurasia oceanic basins reveals for the first time quantitatively, i.e. including uncertainties, the implications of several large-scale tectonic events on the geology of northeast Asia. After a period of compression in Late Cretaceous that led to folding in the Verkhoyansk Mountains, the boundary between North America and Eurasia was subjected to complex tectonic regimes as part of diffuse plate boundary deformation.

Our work illustrates the utility of quantitative kinematic models based on marine geophysical data to unravel the history of superimposed continental deformation events through geological time with tight uncertainties, even if the plate boundary is diffuse and close to the rotation pole. This is particularly useful as a simple rheological consideration shows that continental diffuse plate boundaries are subjected to more complex deformations that could overprint the effects of relative motion of the surrounding rigid plates. The temporal and spatial changes in relative plate motion between Eurasia and North America in northeast Asia (Fig. 5) indicate that the plate boundary changed from a distinct to a diffuse state at about 40 Ma. We used available geological and geophysical information to 'ground truth' the outcome of our model.

The formation of a series of grabens in the Cenozoic in the Laptev Sea seems to agree with approximately 600 km of extension from latest Late Cretaceous to present predicted by our model. The inception of the Moma Rift corresponds to a period of extension predicted by our model that lasted for about 30 Ma (between chrons 31 and 18). Various faults and thrusts observed in the Cherskii Mountains and Moma Rift were the result of compressional and transpressional regimes that characterized the central northeast Asia from Oligocene to present. The location of our stage pole for chron 5 (11 Ma) to present cannot predict the recent tectonic regime that might have changed about 3 Myr ago (and therefore cannot explain the Pliocene deformation of the Moma Rift).

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References

[1] R.G. Gordon, The plate tectonic approximation: Plate nonrigidity, diffuse plate boundaries, and global plate reconstructions, Annu. Rev. Earth Planet. Sci. 26 (1998) 615–642.

[2] M.E. Chapman, S.C. Solomon, North American-Eurasian plate boundary in Northeast Asia, J. Geophys. Res. 81 (1976) 921–930.

[3] R. Macnab, J. Verhoef, W. Roest, J. Arkani-Hamed, New database documents the magnetic character of the Arctic and North Atlantic, EOS 76 (1995) 449, 458.

[4] D.T. Sandwell, W.H.F. Smith, Marine gravity anomaly from Geosat and ERS-1 satellite altimetry, J. Geophys. Res. 102 (1997) 10039–10054.

[5] W.C.I. Pitman, M. Talwani, Seafloor spreading in the North Atlantic, Geol. Soc. Am. Bull. 83 (1972) 619–646.

[6] S.P. Srivastava, Evolution of the Eurasian Basin and its implication to the motion of Greenland along Nares Strait, Tectonophysics 114 (1985) 29–53.

[7] S.P. Srivastava, C.R. Tapscott, Plate kinematics of the North Atlantic, in: P.R. Vogt, B.E. Tucholke (Eds.), The Western North Atlantic Region, The Geology of North America M, Geol. Soc. Am., 1986, pp. 379–405.

[8] D.B. Rowley, A.L. Lottes, Plate-kinematic reconstructions of the North Atlantic and Arctic Late Jurassic to present, Tectonophysics 155 (1988) 73–120.

[9] L.A. Lawver, R.D. Müller, S.P. Srivastava, W. Roest, The opening of the Arctic Ocean, in: U. Bleil, J. Thiede (Eds.), Geologic History of the Polar Oceans: Arctic Versus Antarctic, from the NATO Symposium (October, 1988), Bremen, 1990, pp. 29–62.

[10] S.C. Cande, D.V. Kent, Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, J. Geophys. Res. 100 (B4) (1995) 6093–6095.

[11] D.B. Cook, K. Fujita, C.A. McMullen, Present-day plate interactions in northeast Asia: North American, Eurasian and Okhotsk plates, J. Geodyn. 6 (1986) 33–51.

[12] A.F. Grachev, Moma continental rift (Northeast USSR), Geophyz. Metod. Razved. Arkt. 8 (1973) 56–75.

[13] K. Fujita, F.W. Cambray, M.A. Velbel, Tectonics of the Laptev Sea and Moma rift systems, northeastern USSR, Mar. Geol. 93 (1990) 95–118.

[14] G.P. Avetisov, Geodynamics of the zone of continental continuation of Mid-Arctic earthquakes bel (Laptev Sea), Phys. Earth Planet. Inter. 114 (1999) 59–70.

[15] S.S. Drachev, L.A. Savostin, V.G. Groshev, I.E. Bruni, Structure and geology of the continental shelf of the Laptev Sea, Eastern Russian Arctic, Tectonophysics 298 (1998) 357–393.

[16] V.S. Imaev, L.P. Imaeva, B.M. Koz'min, Seismotectonic dislocations in seismic belts of Yakutia, Geotectonics 29 (1995) 73–86.

[17] S.A. Riegel, K. Fujita, B.M. Koz'min, V.S. Imaev, D.B. Cook, Extrusion tectonics of the Okhotsk plate, northeast Asia, Geophys. Res. Lett. 20 (1993) 607–610.

[18] B.F. Watson, K. Fujita, Tectonic evolution of Kamchatka and the Sea of Okhotsk and implications for the Pacific Basin, in: D.G. Howell (Ed.), Tectonostratigraphic Terranes of the Circum-Pacific Region, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series 1, Houston, TX, 1985, pp. 333–348.

[19] W.J. Nokleberg, L.M. Parfenov, J.W.H. Monger, I.O. Norton, A.I. Khanchuk, D.B. Stone, D.W. Sholl, K. Fujita, Phanerozoic tectonic evolution of the circum-north Pacific, U.S. Geological Survey, 1998.

[20] L. Jolivet, J.P. Cadet, F. Lalevee, Mesozoic evolution of Northeast Asia and the collision of the Okhotsk microcontinent, Tectonophysics 149 (1988) 89–109.

[21] G. Kimura, K. Tamaki, Collision rotation, and back-arc spreading in the region of the Okhotsk and Japan seas, Tectonics 5 (1986) 389–401.

[22] J.-Y. Royer, T. Chang, Evidence for relative motions between the Indian and Australian plates during the last 20 m.y. from plate tectonic reconstructions: implications for the deformation of the Indo-Australian plate, J. Geophys. Res. 96 (B7) (1991) 11779–11802.

[23] B.H. Kirkwood, J.Y. Royer, T.C. Chang, R.G. Gordon, Statistical tools for estimating and combining finite rotations and their uncertainties, Geophys. J. Int. 137 (1999) 408–428.

[24] R.D. Müller, W.R. Roest, Fracture zones in the North Atlantic from combined Geosat and Seasat data, J. Geophys. Res. 97 (B3) (1992) 3337–3350.

[25] J.-Y. Royer, R.G. Gordon, C. DeMets, P.R. Vogt, New limits on the motion between India and Australia since chron 5 (11 Ma) and implications for lithospheric deformation in the equatorial Indian Ocean, J. Geophys. Int. 129 (1997) 41–74.

[26] C. Gaina, R.D. Müller, J.-Y. Royer, J. Stock, J. Hardebeck, P. Symonds, The tectonic history of the Tasman Sea: a puzzle with 13 pieces, J. Geophys. Res. 103 (1998) 12413–12433.

[27] L.P. Zonenshain, M.I. Kuzmin, L.M. Natapov, Geology

of the USSR: A plate tectonic synthesis, American Geophysical Union, Washington, DC, 1990.

[28] V.A. Vinogradov, Laptev Sea, in: I.S. Gramberg, Y.E. Pogrebitskii (Eds.), Geologic Structure of the USSR and its Relationship to the Distribution of Mineral Resources, Seas of the Soviet Arctic 9, Leningrad, 1984, pp. 51–60.

[29] S.S. Drachev, G.L. Johnson, S.W. Laxon, D.C. McAdoo, H. Kassens, Main structural elements of eastern Russian Arctic continental margin derived from satellite gravity and multichannel seismic data, in: H. Kassens, H.A. Bauch, I. Dmitrenko, H. Eicken, H.-W. Hubberten, M. Melles, J. Thiede, L. Timokhov (Eds.), Land–Ocean Systems in the Siberian Arctic: Dynamics and History, Springer, Berlin, 1999, pp. 667–682.

[30] L.M. Parfenov, Tectonics of the Verkhoyansk-Kolyma Mesozoides in the context of plate tectonics, Tectonophysics 199 (1991) 319–342.

[31] L.M. Parfenov, A.V. Prokopiev, V.V. Gaiduk, Cretaceous frontal thrusts of the Verkhoyansk fold belt, eastern Siberia, Tectonics 14 (1995) 342–358.

[32] L.P. Zonenshayn, L.M. Natapov, L.A. Savostin, A.P. Stausuii, Recent plate tectonics of northeastern Asia in connection with the opening of the North Atlantic and Arctic Ocean Basins, Oceanology 18 (1978) 550–555.

[33] L.M. Parfenov, B.M. Koz'min, O.V. Grinenko, V.S. Imaev, L.P. Imaeva, Geodynamics of the Chersky seismic belt, J. Geodyn. 9 (1988) 15–37.

[34] V.S. Imaev, L.P. Imaeva, B.M. Koz'min, A.A. Surnin, K. Fujita, Seismically active strike-slip faults as generators of modern pull-apart basins in Northeast Asia, in: AGU Fall meeting, A.G. Union, ed., EOS Trans. 44, American Geophysical Union, San Francisco, CA, 1994, pp. 631.

[35] Y.A. Kosygin, L.M. Parfenov, Tectonics of the Soviet Far East, in: A.E.M. Nairn, M.J. Churkin, F.G. Stehli (Eds.), The Arctic Ocean, The Ocean Basins and Margins vol. 5, Plenum Press, New York, 1981, pp. 377–412.

[36] L.A. Savostin, A.M. Karasik, Recent plate tectonics of the Arctic Basin and of northeastern Asia, Tectonophysics 74 (1981) 111–145.

[37] K.G. Mackey, K. Fujita, L.J. Ruff, Crustal thickness of northeast Asia, Tectonophysics 284 (1998) 283–297.

[38] E. Gordeev, M. Kasahara, V. Levin, H. Takahashi, V. Bakhtiarov, V. Chebrov, A. Gusev, V. Pavlov, Deformation at the Eurasia-Pacific-North America plate junction from GPS data, in: AGU Fall Meeting, A.G. Union, ed., EOS Trans. 81, American Geophysical Union, San Francisco, CA, 2000.

[39] M.B. Gordon, Diffuse oceanic plate boundaries: strain rates, vertically averaged rheology, and comparisons with narrow plate boundaries and stable plate interiors, in: M.A. Richards, M.B. Gordon, R.D. van der Hilst (Eds.), The History and Dynamics of Global Plate Motions, Geophysical Monograph 121, American Geophysical Union, Washington, DC, 2000, pp. 145–159.

[40] K.S. Krishna, D. Gopala Rao, M.V. Ramana, V. Subrahmanyam, K.V.L.N.S. Sarma, A.I. Pilipenko, V.S. Shcherbakov, I.V. Radhakrishna Murthy, Tectonic model for the evolution of oceanic crust in the northeastern Indian Ocean from the Late Cretaceous to the early Tertiary, J. Geophys. Res. 100 (B10) (1995) 20011–20024.

[41] K.M. Larson, J.T. Freymueller, S. Philipsen, Global plate velocities from the Global Positioning System, J. Geophys. Res. Solid Earth 102 (B5) (1997) 9961–9981.

[42] M.L. Zoback, First- and second-order patterns of stress in the lithosphere: The World Stress Map Project, J. Geophys. Res. 97 (1992) 11703–11728.

[43] P. England, P. Molnar, Inferences of deviatoric stress in actively deforming belts from simple physical models, Philos. Trans. R. Soc. Lond. 337 (1991) 151–164.

[44] L.J. Sonder, P. England, Vertical averages of rheology on large scale continental extension, Earth Planet. Sci. Lett. 77 (1986) 81–90.

[45] V.S. Imaev, L.P. Imaeva, B.M. Koz'min, L.V. Gunbina, K.G. Mackey, K. Fujita, Seismicity and present day boundaries of plates and blocks in northeast Asia, Geotectonics 34 (4) (2000) 44–51.

[46] J.P. Jemsek, E.A. Bergman, J.L. Nabelek, S.C. Solomon, Focal depths and mechanisms of large earthquakes on the Arctic mid-ocean ridge system, J. Geophys. Res. 91 (1986) 13993–14005.