JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, B07106, doi:10.1029/2003JB002687, 2004

Geology of the East Siberian Sea, Russian Arctic, from seismic images: Structures, evolution, and implications for the evolution of the Arctic Ocean Basin

Dieter Franke, Karl Hinz, and Christian Reichert

Federal Institute for Geosciences and Natural Resources, Hannover, Germany

Received 14 July 2003; revised 14 April 2004; accepted 11 May 2004; published 23 July 2004.

[1] The kinematics and history of the opening of the Amerasia Basin are closely linked to the geology of the wide shelves surrounding the Arctic Ocean. In this context, multichannel seismic reflection data from the virtually unexplored shelf of the East Siberian Sea, Russian Arctic, are discussed in combination with potential field data. Three seismic marker horizons were defined and mapped. Their ages were linked to main tectonic and regional events and to onshore findings. The data reveal that there is no continuation of the large rift basins from the Laptev Shelf onto the East Siberian Shelf and there are no indications for the previously defined several hundred kilometers wide Blagoveshchensk Basin. The East Siberian Shelf is best described as an epicontinental platform that synsedimentarily subsided continuously since Late Cretaceous times with stronger subsidence to the northeast, resulting in the formation of a large depocenter. Some form of extensional/transtensional stresses affected the area and created relatively small ESE–WNW striking basins within this depocenter. These basins are filled with >6 km thick Late Cretaceous to Tertiary sediments. The general dip of the platform of the East Siberian Shelf toward the northeast may be explained by dip-slip movements along a major transform fault that is proposed by the rotation model for the opening of the Amerasia Basin. For the evolution of small sag-shaped basins within the East Siberian Depocenter we suggest a link to the opening of the Eurasia Basin instead of to the opening of the Makarov Basin. *INDEX TERMS:* 8109 Tectonophysics: Continental tectonics—extensional (0905); 8015 Structural Geology: Local crustal structure; 9315 Information Related to Geographic Region: Arctic region; 3025 Marine Geology and Geophysics: Marine seismics (0935); 3040 Marine Geology and Geophysics: Plate tectonics (8150, 8155, 8157, 8158); *KEYWORDS:* East Siberian Shelf, Russian Arctic, seismic data

Citation: Franke, D., K. Hinz, and C. Reichert (2004), Geology of the East Siberian Sea, Russian Arctic, from seismic images: Structures, evolution, and implications for the evolution of the Arctic Ocean Basin, *J. Geophys. Res.*, *109*, B07106, doi:10.1029/2003JB002687.

1. Introduction

1.1. Scope of the Paper

[2] The kinematics and history of the opening of the Arctic Ocean Basin, comprising the Eurasia and the geologically more complex Amerasia Basins, in Mesozoic and early Tertiary times are first-order scientific problems awaiting solution in the Arctic. Present knowledge, especially of the geologic framework of the Amerasia Basin and its continental margins, is insufficient for solving the problems due to the polar ice pack which precludes the acquisition of the required geophysical data from conventional research vessels. However, an understanding of the geology of the wide shelves surrounding the Arctic Ocean Basin and an extrapolation of the geological features from the shelves could provide significant insight into the tectonic character of the Amerasia Basin and would also facilitate a testing of the numerous competing circum-Arctic plate tectonic models extensively reviewed by *Lawver and Scotese* [1990].

[3] The up to 800 km wide East Siberian Shelf is a virtually unexplored area, and most geological models for this shelf are extrapolations of the geology of the New Siberian Islands, the Wrangel Island, and the northeast Siberia landmass. Apart from few seismic reflection lines (see section 2.2), airborne magnetic data were the primary means of deciphering the structural pattern of the East Siberian Shelf. Summaries of the geology and models for the tectonic evolution are given by *Fujita and Newberry* [1982], *Savostin et al.* [1984], *Fujita and Cook* [1990], *Parfenov et al.* [1993], and *Drachev et al.* [1999].

[4] In this paper we present the results of our seismic reflection studies on the shelf of the East Siberian Sea and the conclusions that can be drawn with respect to existing hypotheses. The study area is located between the New

0148-0227/04/2003JB002687$09.00

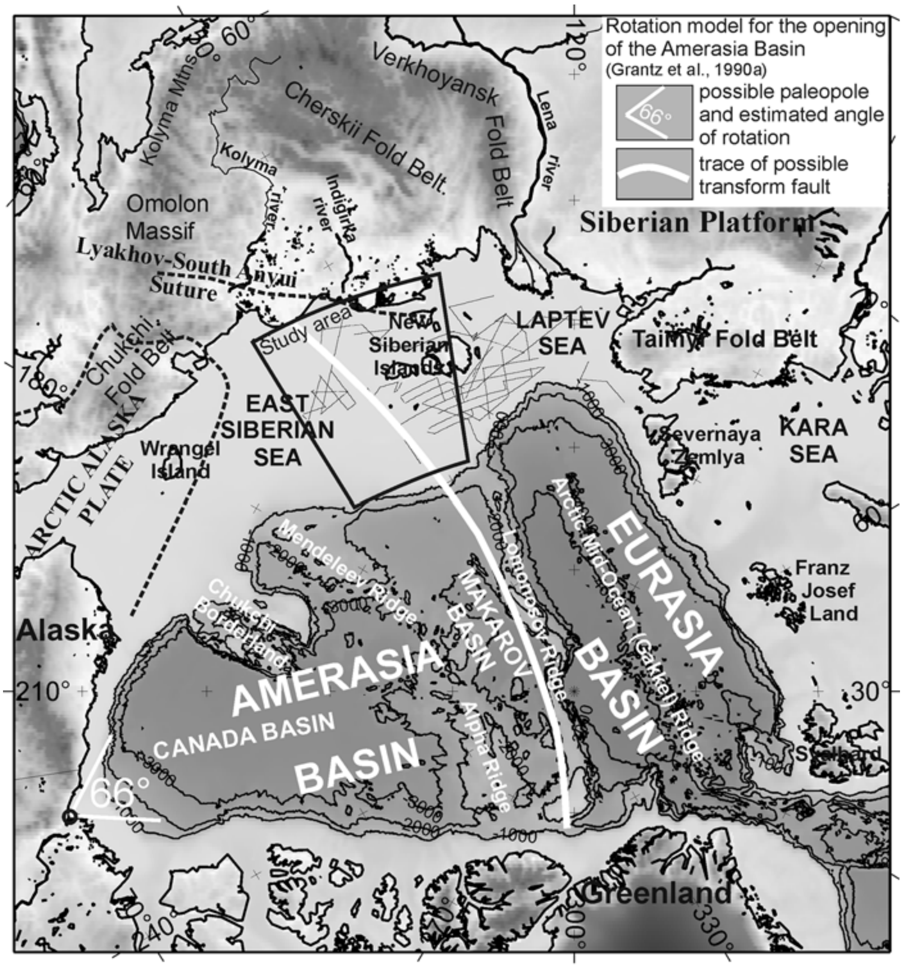

Figure 1. Main onshore Phanerozoic features and marine nomenclature of the Arctic Ocean Basin [*Grantz et al.*, 1990a, 1990c; *Khain*, 1994]. The white thick solid line represents the approximate location of a major transform fault predicted in the rotation model for the opening of the Amerasia Basin [*Grantz et al.*, 1990a]. The area under study and BGR's multichannel reflection seismic lines (thin solid black lines) are indicated.

Siberian Islands and the De Long Islands to the west and Wrangel Island to the east. To the north the continental margin is bordered by the Amerasia Basin, which is subdivided by the Alpha-Mendeleev Ridge into the Canada Basin and the Makarov Basin (Figure 1). The opening of the latter may have affected the geology of the East Siberian Shelf [e.g., *Grantz et al.*, 1990a; *Drachev et al.*, 1999] as well as the proposed accretion of several terranes [e.g., *Fujita and Newberry*, 1982; *Parfenov et al.*, 1993] to the paleo-Siberian continental margin.

1.2. Evolution of the Amerasia Basin

[5] Conclusive evidence to derive the age and evolution of an oceanic basin is mainly derived from the identification of magnetic spreading anomalies, spreading centers, and fracture zones. Regarding the Eurasia Basin (Figure 1), there is general consensus that the opening was initiated with the splitting of the North America-Eurasia lithospheric plates during the Late Cretaceous and that the Eurasia Basin opened along the Gakkel Ridge at time of magnetic anomaly 24/25 (52.4–55.9 Ma; timescale here and in the following is according to *Cande and Kent* [1995]) [e.g., *Srivastava and Tapscott*, 1986; *Rowley and Lottes*, 1988; *Kristoffersen*, 1990; *Jackson and Gunnarsson*, 1990].

[6] In the nearly 4000 m deep Amerasia Basin, comprising the elongated Makarov Basin and the broader Canada Basin (Figure 1), seafloor spreading anomalies are difficult to analyze because of their relatively low amplitude [*Grantz et al.*, 1990a] and because they may be masked in parts by the thick volcanic succession of Alpha Ridge [*Vogt et al.*, 1982]. However, *Vogt et al.* [1979] started to present a model for the Mesozoic evolution of the Arctic based on magnetic data, and in the following, of the three end-member models for the formation of the Amerasia Basin, oceanization of continental crust, entrapment of old oceanic crust, and in situ formation of Mesozoic or Cenozoic oceanic crust, only the last is seriously discussed [*Lawver and Scotese*, 1990]. With this precondition the most popular model for the evolution of the Amerasia Basin invokes a counterclockwise rotational opening that preliminary bases on a match of geological lineaments on both sides of the deep oceanic basin and paleomagnetic data [e.g., *Grantz et al.*, 1990a; *Lawver and Scotese*, 1990; *Embry*, 2000]. The rotational hypothesis requires that a large transform fault

system along the boundary between the Lomonosov Ridge and the Makarov Basin must cross the western part of the East Siberian Sea and extend into northeastern Siberia near 155° longitude, between Indigirka and Kolyma Rivers [*Grantz et al.*, 1990a] (compare Figure 1). In the past 10 years more detailed models were developed to explain the newly available data. *Lane* [1997] rejected the rotation model and introduced a multistage kinematic model with varying extinct spreading axes in the Amerasia Basin, while *Embry* [2000] presented a modified rotation model with three main segments of spreading separated by transform faults. In the latter model a major transform fault is still supposed to cross the western part of the East Siberian Shelf [*Embry*, 2000].

[7] The Makarov Basin, which lies between the Lomonosov Ridge and the Alpha-Mendeleev Ridge, probably was created by crustal stretching that may have included seafloor spreading west of 160°W [*Weber and Sweeney*, 1990]. The place of the Makarov Basin in the tectonic chronology of the Arctic region is still puzzling. It probably formed in the interval between the opening of the Canada Basin and initiation of seafloor spreading in the Eurasia Basin, i.e., between 118 and 56 Ma [*Weber and Sweeney*, 1990]. *Taylor et al.* [1981] published the first suggestions on seafloor spreading anomalies in the Makarov Basin and hypothesized that the basin was opening from Late Cretaceous through the Paleocene (84–49 Ma) along an axis about coincident with the 87°N parallel of latitude. According to *Weber and Sweeney* [1990], peneplanation and subsequent subsidence of the complex Mesozoic-Paleozoic basement of the East Siberian Shelf might be due to the early opening and the subsequent episode of seafloor spreading in the Makarov Basin.

1.3. Regional Setting of the East Siberian Shelf

[8] In between the proposed extension of the Arctic Alaska plate to northeastern Siberia (Figure 1) [*Grantz et al.*, 1990a] and the Siberian Platform a collage of allochthonous paleoplates is supposed [e.g., *Fujita and Newberry*, 1982; *Zonenshain et al.*, 1990; *Fujita and Cook*, 1990; *Grantz et al.*, 1990a]. The accretion of these terranes to the paleo-Siberian continental margins in the Mesozoic [*Parfenov et al.*, 1993] resulted in the formation of several large fold belts (Figure 1), namely, the Taimyr, Verkhoyansk, Cherskii, and Chukchi fold belts [e.g., *Fujita and Newberry*, 1982; *Savostin et al.*, 1984; *Zonenshain et al.*, 1990; *Fujita and Cook*, 1990; *Parfenov*, 1991; *Khain*, 1994]. The fold belts underwent intensive pervasive deformation and were intruded by granitic plutons during the Mid-Jurassic to Lower Cretaceous. A period of leveling followed which resulted in the formation of widespread planar surfaces and weathering horizons in the entire region [e.g., *Khain*, 1994]. *Fujita and Newberry* [1982] suggest that subsequent ample sediment was supplied from the surrounding regions onto the shelf of the East Siberian Sea starting in the Late Cretaceous. Moreover, they suppose that parts of the East Siberian Shelf may be underlain by oceanic crust that was trapped between the Siberian craton, the Arctic-Alaska plate, and the Omolon terrane. The latter comprises the area around the Omolon Massif (Figure 1). The mid-Cretaceous plate collision is thought to have created the formation of the ophiolitic Lyakhov–South Anyui Suture [*Savostin et al.*, 1984; *Fujita and Cook*, 1990; *Drachev and Savostin*, 1993] located in between the Verkhoyansk fold belt and the New Siberian Islands-Chukchi region (Figures 1 and 2). The southern islands from the New Siberian Islands group, namely, the Malyi and Bol'schoi Lyakhov Islands, are assumed as part of Lyakhov–South Anyui Suture [*Kos'ko and Trufanov*, 2002]. The presence of three several hundred kilometers wide, roughly east-west trending basins has been interpreted beneath the East Siberian Shelf on the basis of aeromagnetic data (Figure 2). Their subsurface structure has been estimated from the computation of depth to the magnetic basement. They were named Blagoveshchensk, New Siberian (Figure 3), and Vil'kitskii basins and are believed to be filled primarily with Paleozoic to Mesozoic, and possibly some Cenozoic, sediments [*Kos'ko*, 1984]. The study area forms part of a shelf region named Novaya Sibir' Terrane [*Fujita and Cook*, 1990] and Faddeya Domain [*Kos'ko and Trufanov*, 2002], respectively. These domains comprise the central New Siberian Islands Novaya Sibir' and Faddeya (compare Figure 4) and offshore extrapolations. The oldest rocks exposed or drilled on Faddeya Island and Novaya Sibir' Island are of Jurassic to Eocene age [*Kos'ko and Trufanov*, 2002]. On the northern side of the study area is the De Long Domain, which comprises the area of the De Long Islands: Vil'kitskii, Benett, Zhokhov, Henrietta, and Jeanette Island (Figures 2 and 4). The area is characterized by Cretaceous and Neogene alkali-rich basaltic extrusives [e.g., *Kos'ko and Trufanov*, 2002], and beyond the De Long Domain lies the Makarov Basin.

2. Geophysical Data

2.1. Aeromagnetic and Satellite-Derived Altimeter Data

[9] *Verhoef et al.* [1996] compiled all the available magnetic data over the whole North Atlantic and Arctic region. Satellite radar altimetry derived the marine gravity field to latitudes of 82°N by accurate measurements of the average sea surface topography and reprocessing of the individual echoes to overcome the problem of an ice cover [*Laxon and McAdoo*, 1994]. The southern Makarov Basin appears as a smooth low in the gravity field with no clear structural segments (Figure 2, top). In the magnetic data (Figure 2, bottom) the southern boundary of the East Siberian Sea is marked by a west-northwest striking band of anomalies which trend in strike with the Lyakhov–South Anyui Suture. The De Long Domain, to the north of the study area, is the most striking feature in both the magnetic (amplitudes up to 800–1000 nT) and the gravity data (Figure 2). The large ellipsoid-shaped positive feature is assumed to represent the extension of Cretaceous and Neogene alkali-rich basaltic extrusives [e.g., *Kos'ko and Trufanov*, 2002] that may be due to hot spot related intraplate volcanism [*Fujita and Cook*, 1990]. The anomalies damp out to the north and do not reach the continental slope of the Makarov Basin.

[10] Apart from linear, east-west striking magnetic anomalies of 250–500 nT northwest of Wrangel Island the magnetic filed is generally quiet in the East Siberian Sea. The gravity data in contrast show several lows in the East Siberian Sea (Figure 2, top). While the area of the

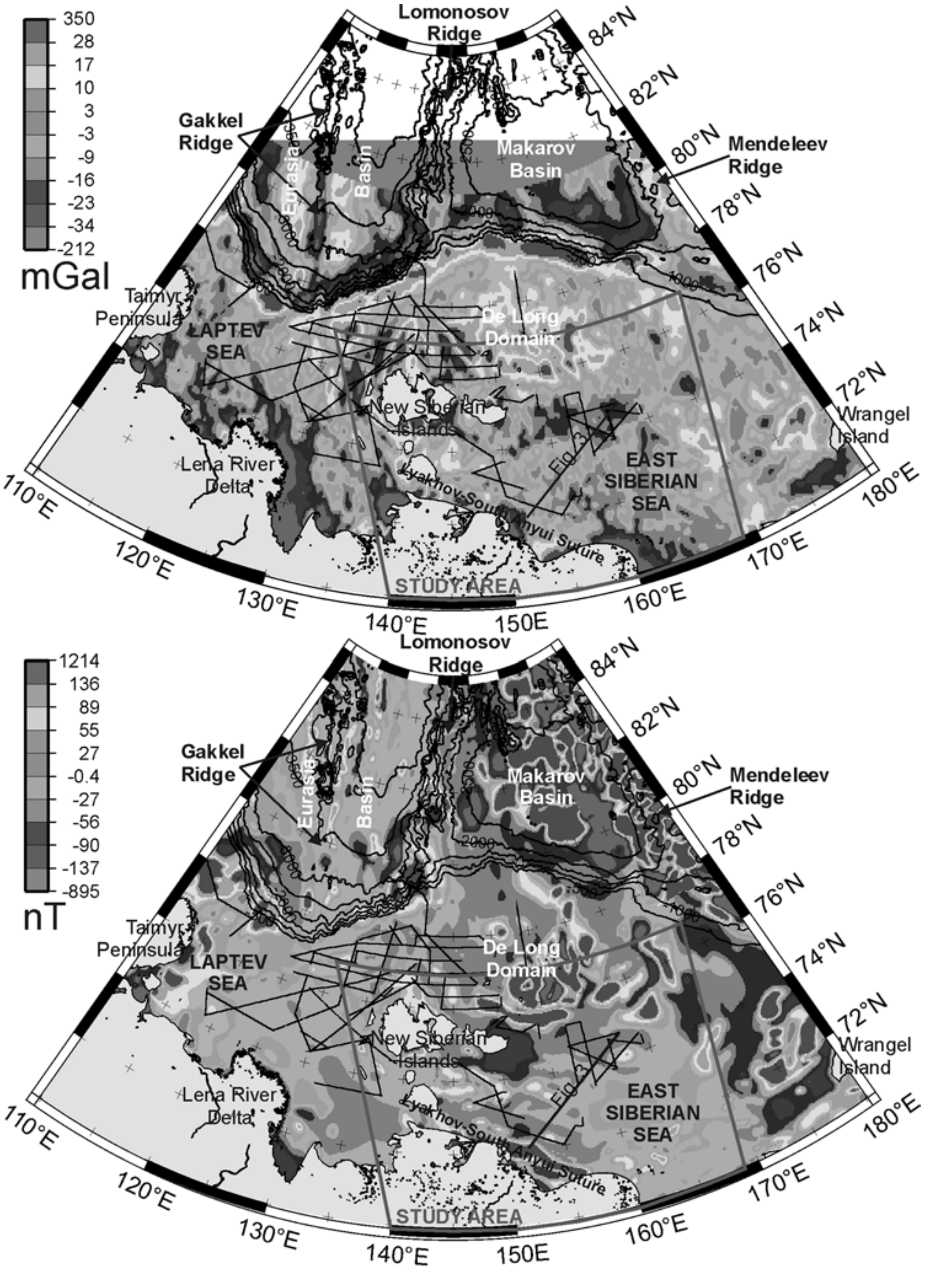

Figure 2. (top) Altimeter-derived marine gravity field to latitude of 82°N [*Laxon and McAdoo*, 1994] and (bottom) airborne magnetic data [*Verhoef et al.*, 1996]. The main structural elements of the eastern Russian Arctic are marked. The area under study and BGR's multichannel reflection seismic (MCS) lines are indicated. See color version of this figure at back of this issue.

previously defined Blagoveshchensk Basin, postulated to stretch several hundred kilometers from south of the eastern New Siberian Islands onto the East Siberian Shelf [e.g., *Kos'ko et al.*, 1993] (compare Figure 3), is generally positive, the gravity field smoothly becomes negative over the inferred southern extension of the New Siberian Basin.

2.2. Seismic Reflection Data

[11] So far, the only published multichannel seismic reflection data (MCS) from the western East Siberian Sea are three lines (by Marine Arctic Geological Expedition (MAGE)) (located between 76.5°N and 79.5°N, 152°E and 164°E; compare Figure 4) covering an area from the De Long Uplift to the middle continental slope of the Makarov Basin [*Sekretov*, 2001], and a line drawing of the MCS line LARGE 98001 running from the Indigirka Bay toward Jeanette Island, De Long Uplift [*Drachev et al.*, 1999].

[12] The Federal Institute for Geosciences and Natural Resources (BGR) in cooperation with Sevmorneftegeofizika (SMNG) carried out a seismic survey on the shelf of the East Siberian Sea between longitudes 147° and 165°E in 1994 (cruise BGR94), using the research vessel M/V

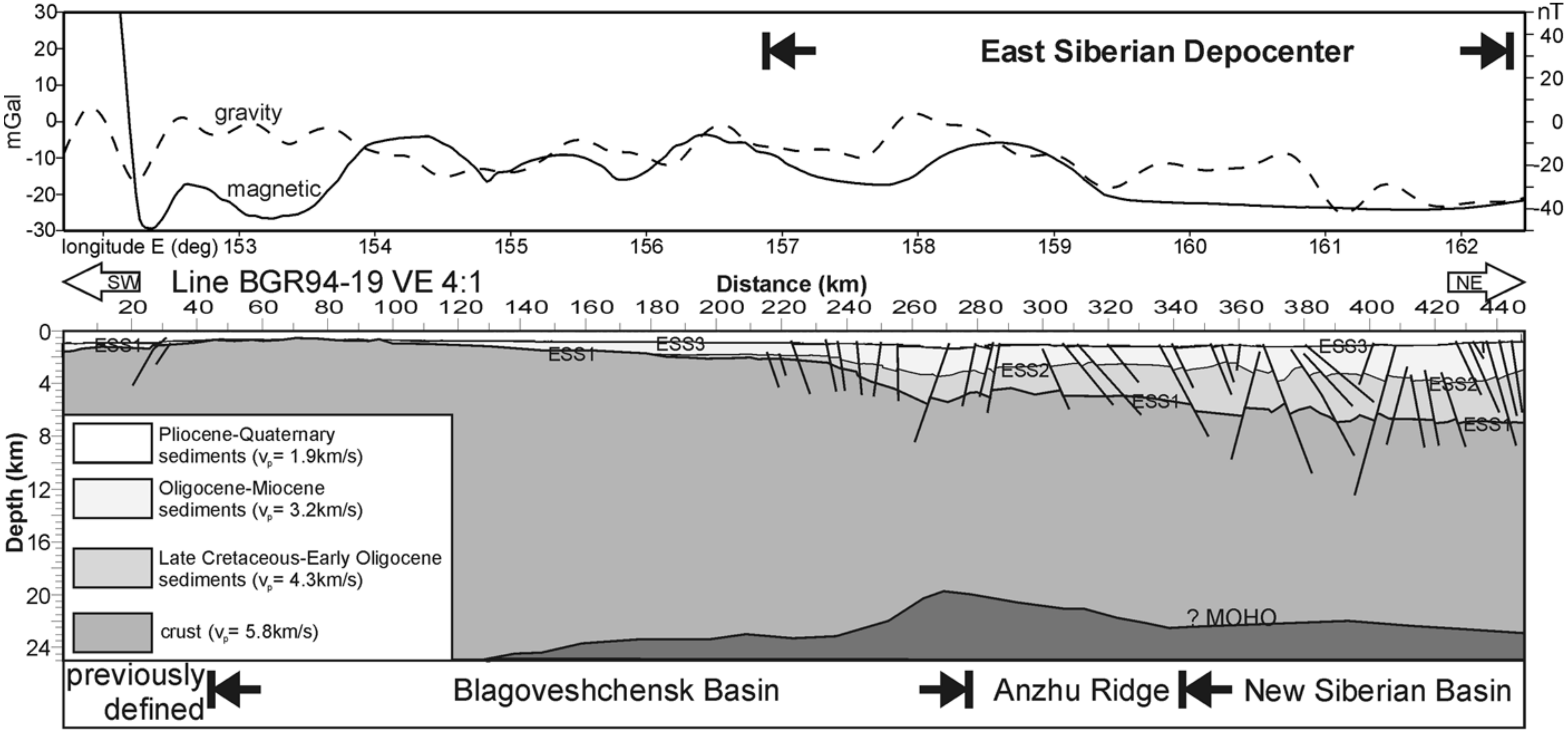

Figure 3. (bottom) Simplified crustal section of line BGR94-19 from the East Siberian Shelf. (top) Free-air gravity (dashed) and magnetic field (solid). The reflection seismic data were depth converted using averaged interval velocities. Along this line previously defined structural elements are indicated below the section [e.g., *Kos'ko et al.*, 1993]. ESS1, ESS2, and ESS3 indicate the different marker horizons (see text). The extension of the East Siberian Depocenter is shown. For location of the line see Figure 2.

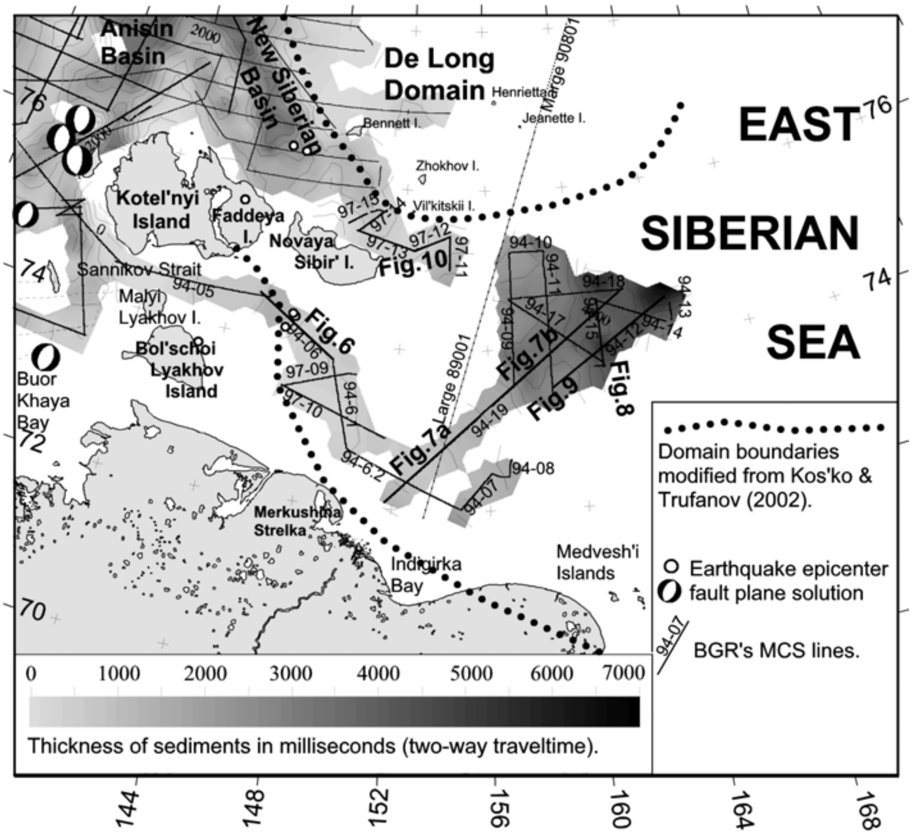

Figure 4. Thickness of sediments (depth of horizon ESS1) in milliseconds (two-way travel time). The dotted black lines mark the domain boundaries (modified from *Kos'ko and Trufanov* [2002]). Earthquake epicenters [*Engdahl et al.*, 1998] and fault plane solutions are indicated [*Franke et al.*, 2000]. The dashed lines indicate the locations of MCS profiles Large89001 [*Drachev et al.*, 1999] and the southern part of line Marge90801 [*Sekretov*, 2001]. Locations of the seismic lines illustrated and discussed in the text are indicated.

Akademik Nemchinov. The scientific objective was to reveal the structural style of that virtually unexplored East Siberian Shelf. Although adverse ice conditions often hampered the survey, ~2609 km of MCS data have been acquired on the East Siberian Shelf south of latitude 76°N. In addition, an ~496 km long seismic line was surveyed in 1994 along the Sannikov Strait that separates the New Siberian Islands in the north from the Lyakhov Islands in the south. This line provides a tie between our East Siberian data and our data set on the Laptev Shelf (Figure 4) [see also *Franke et al.*, 2001]). Another MCS survey carried out by the BGR in 1997 off Siberia (cruise BGR97 [*Hinz et al.*, 1998]) added ~559 km of seismic data.

[13] Seismic field parameters and processing of BGR's 1997 cruise is described by *Franke et al.* [2001]. The parameters for the 1994 survey were the following: (1) seismic source, sleeve gun array consisting of three linear subarrays with eight guns each (total volume 36.8 L), (2) recording system, analogue AMG streamer with 118 channels and an active length of 2959 m, SERCEL SN 358 DMX recording unit, (3) recording parameter, recording length of 12 s, sampling rate of 4 ms, (4) navigation and positioning system, Geophysical Integrated Navigation System (GIN3), and (5) processing sequence, standard with common depth point (CDP) sorting, velocity analysis, normal moveout (NMO) corrections, muting and stacking, and steep dip finite difference time migration.

3. Interpretation

3.1. Acoustic Basement

[14] Our seismic reconnaissance lines show a well-layered succession that increases gradually in thickness from around 1 s two-way travel time (twt) at about 73°N, 155°E in the south to ~4 s twt in the north in front of the southern flank of the De Long Uplift; that is, the sedimentary thickness increases by ~6000 m (Figure 4). The layered succession rests on an acoustic basement mostly lacking an internal coherent reflection pattern. The general seismic characteristics of the top of the acoustic basement are as follows: It is, in general, clearly imaged, and it dips slightly to the north albeit intervened by some depressions that will be discussed later. The morphology is mainly smooth to flat, suggesting that it was affected by strong truncation and peneplanation prior to subsidence and deposition of the sedimentary overburden. The important reflection horizon, labeled ESS1 (East Siberian Sea 1; compare Figure 5), most probably represents the peneplained surface of the complex folded basement mentioned before. Locally restricted on line BGR94-06, horizon ESS1 bears a hummocky relief

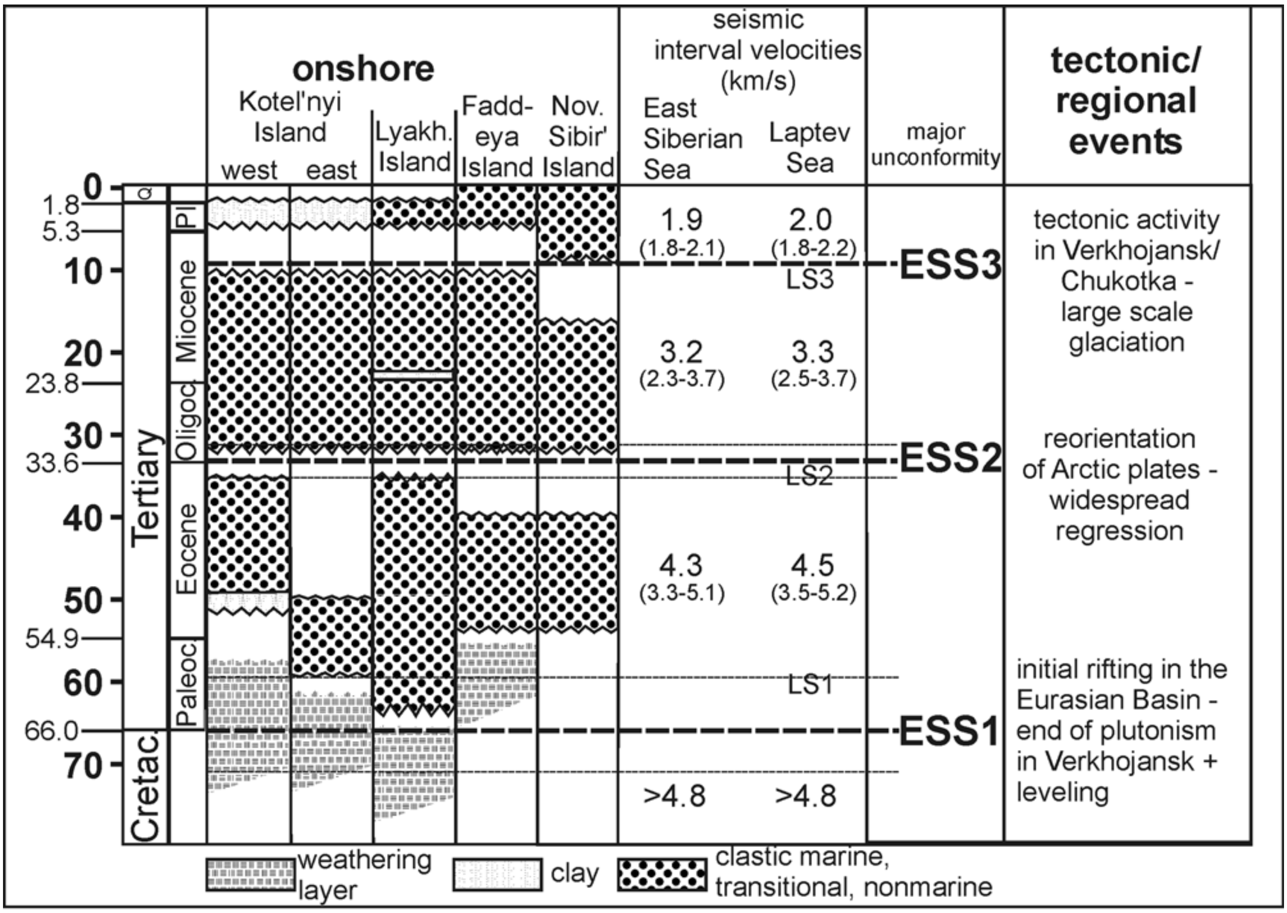

Figure 5. Generalized stratigraphy and lithology of Cenozoic sections from the New Siberian Islands and the adjacent onshore region (adapted from *Kos'ko et al.* [1990], *Alekseev et al.* [1992], *Khain* [1994], and *Kos'ko and Trufanov* [2002]) and main tectonic and regional events. The seismic interval velocities from the East Siberian Sea are shown in comparison to those from the Laptev Sea [*Franke et al.*, 2001]. The ages of the major seismic unconformities ESS1, ESS2, and ESS3 are tentatively linked to the onshore findings and main tectonic events.

with peak to trough amplitudes in the range of 0.1–0.2 s twt (Figure 6, shot points (SP) 1400–1900) that might represent an expression of the Lyakhov–South Anyui Suture [e.g., *Fujita and Cook*, 1990; *Drachev and Savostin*, 1993; *Khain*, 1994]. According to *Weber and Sweeney* [1990], peneplanation and subsequent subsidence of the complex Mesozoic-Paleozoic basement beneath horizon ESS1 might be due to the early opening and the subsequent episode of seafloor spreading in the Makarov Basin from 118 through 56 Ma. However, we tentatively correlate the onset of the regional truncation, manifested in our seismic data as the distinct smooth horizon ESS1 (Figures 6 and 7a) more precisely with the end of the granitoid plutonism in the Verkhochansk-Chukotka folded system in the Late Cretaceous [*Parfenov*, 1991; *Drachev et al.*, 1998] because that instant was followed by a period of leveling evidenced by the formation of extensive planation surfaces as well as weathering horizons and thin coal-bearing limnic sediments [e.g., *Khain*, 1994].

3.2. Layered Reflector Succession

[15] The layered reflector succession representing sediments is subdivided by at least two distinct, regional seismic marker horizons, labeled ESS2 and ESS3, albeit some more but less distinct and less correlatible horizons are present. Because of the absence of deep offshore holes in the entire region the inferred stratigraphy of the defined horizons remains uncertain. However, there is geological and geophysical evidence in favor of our interpretations (Figure 5). The following are of major importance and imply hiatuses

Figure 6. (top) Line drawing interpretation of MCS line BGR94-06 and (bottom) example seismic section showing the region that currently is affected by extension. At this location, three earthquakes occurred within the past 30 years (compare Figure 4). The hummocky relief with peak to trough amplitudes in the range of 0.1–0.2 s twt of horizon ESS1 (SP 1400–1900) may indicate that here the acoustic basement consists of rocks of the Lyakhov-South Anyui Suture. The numbers indicate interval velocities in km/s. For location, see Figure 4.

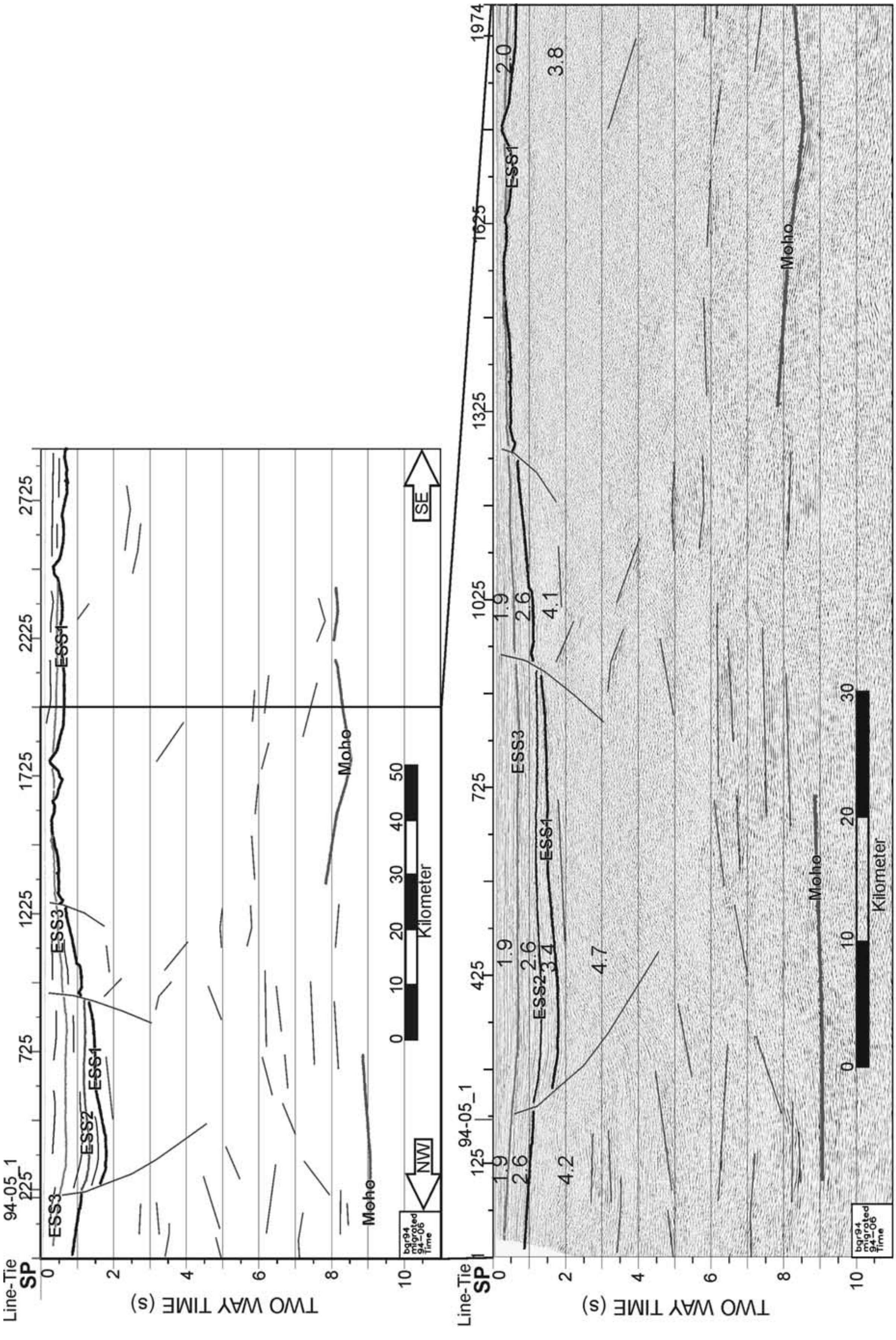
Line-Tie
SP
94-05_1
225
725
1225
1725
2225
2725
ESS3
ESS2
ESS1
Moho
NW
SE
0
10
20
30
40
50
Kilometer
bgr94 migrated 94-06 Time
TWO WAY TIME (s)
0
2
4
6
8
10
1
125
425
725
1025
1325
1625
1974
1.9
2.6
4.2
3.4
4.7
4.1
2.0
3.8
Kilometer

Figure 6

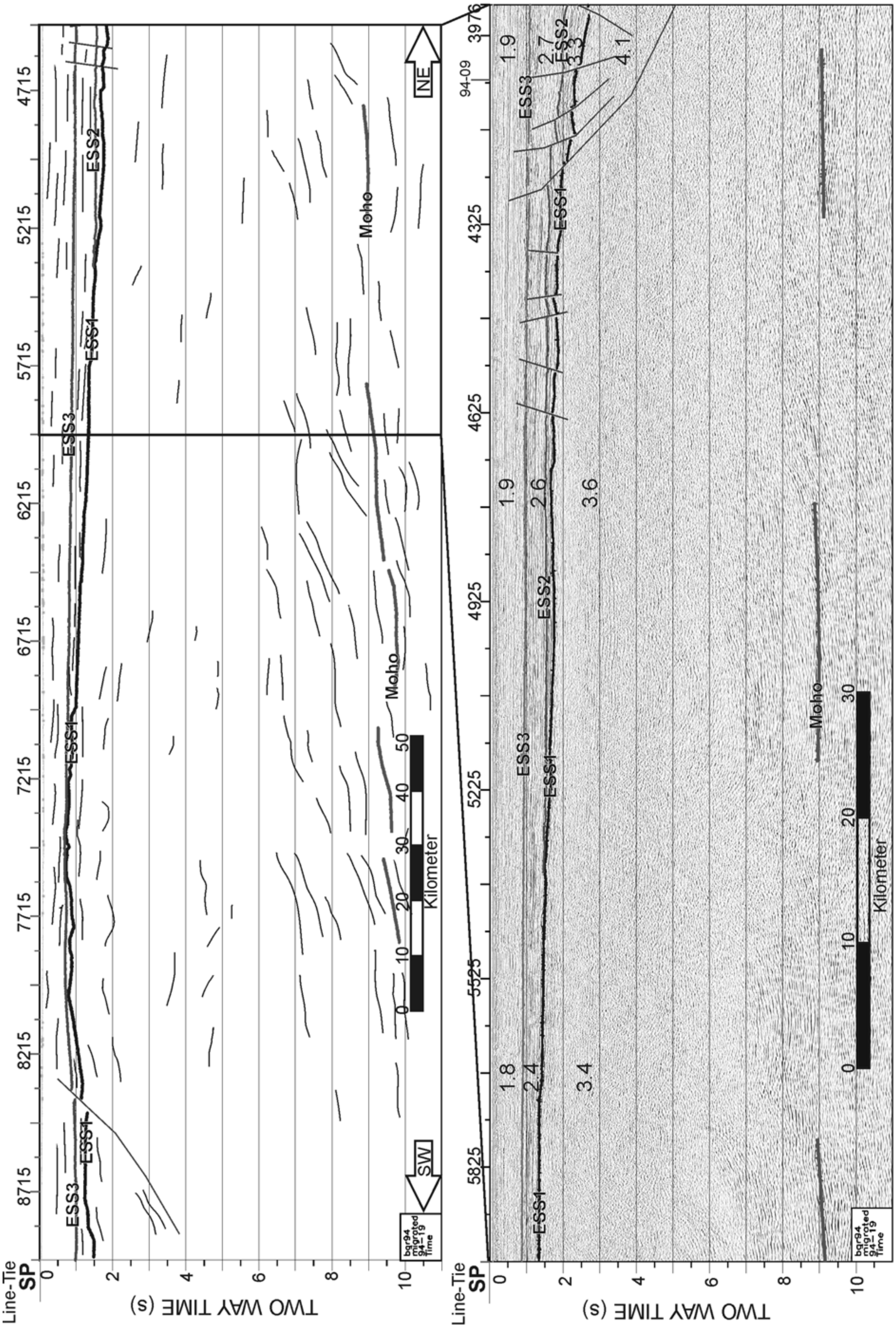
Line-Tie
SP
TWO WAY TIME (s)
0
2
4
6
8
10
4715
5215
5715
6215
6715
7215
7715
8215
8715
ESS1
ESS2
ESS3
Moho
NE
SW
0
10
20
30
40
50
Kilometer
bgr94 migrated 94-19 Time
3976
94-09
4325
4625
4925
5225
5525
5825
1.9
2.7
3.3
4.1
1.9
2.6
3.6
1.8
2.4
3.4
0
10
20
30
Kilometer

Figure 7a

or unconformities that should have corresponding seismic images: (1) the onset of seafloor spreading in the Eurasia Basin during chron 24/25 (early Eocene [e.g., *Srivastava and Tapscott*, 1986; *Rowley and Lottes*, 1988; *Kristoffersen*, 1990; *Jackson and Gunnarsson*, 1990]) and subsequent reorientation of relative plate motions in the circum-Arctic during the early Oligocene [e.g., *Chalmers et al.*, 1993; *Hinz et al.*, 1993], (2) the revival of tectonic activity in the Verkhoyansk-Chukotka region at about the end of the Miocene (e.g., *Khain*, 1994], (3) distinct similarities in the reflection pattern and common seismic characteristics of the sedimentary units of the shelves of the East Siberian Sea (horizons ESS2 and ESS3) and the Laptev Sea (horizons LS2 and LS3), and (4) a proof for the widely extended impact of the mentioned geological events and considerably supports the stratigraphic interpretation.

[16] Horizon ESS2 (Figures 8 and 9, line BGR94-12 and -15) is a highly reflective horizon forming the top of the older depositional unit characterized by a coherent and highly reflective internal layering. Its reflection pattern has very similar characteristics and interval velocities as the LS2 horizon in the Laptev Sea as defined earlier by *Hinz et al.* [1998] and *Franke et al.* [2001]. The seismic interval velocities of the unit between ESS1 and ESS2 were derived from stacking velocities and are around 4.3 km/s. A maximum value of 5.1 km/s was found in the deep subsided graben on line BGR04-12 (Figures 4 and 9). However, on the line perpendicular to that graben (line BGR94-15, Figure 8) the velocity is only 4.6 km/s. This gives an estimate of the inherent uncertainty of seismic velocities derived from stacking velocities. The values that are similar in the Laptev Sea region are rather high for Cenozoic sediments. We note here that seismic measurements on the East Greenland continental margin [*Hinz and Schlüter*, 1980; *Hinz et al.*, 1993] and on exposed bedrock in the Isfjorden area of Svalbard [*Gronlie*, 1977] have determined seismic velocities as high as 4–4.9 km/s for Tertiary sandstones. A more detailed discussion of seismic velocities in the area under discussion is given by *Franke et al.* [2001].

[17] Horizon ESS2 is not recognizable on the lines from the Sannikov Strait and on the shelf region to the south of Novaya Sibir' Island, i.e., between longitudes 145°E and 150°E. The seismic image strongly suggests that ESS2 represents an erosional surface. We infer an early Oligocene age (~33 Ma; compare Figure 5) for horizon ESS2 because an erosional event in the beginning of the Oligocene preceding the deposition of Oligocene-Miocene strata is known from several localities on the New Siberian Islands [e.g., *Kos'ko and Trufanov*, 2002]. A significant reorientation of relative plate motions occurred in this time in the circum-Arctic oceans, when seafloor spreading ceased in the Labrador Sea and separation of NE Greenland from Spitsbergen was initiated along a regional transform fault that linked the Atlantic with the Eurasia Basin [e.g., *Chalmers et al.*, 1993; *Hinz et al.*, 1993]. Moreover, this is in good accordance with a major sea level fall in the early Oligocene [*Haq et al.*, 1988].

[18] Horizon ESS3 (Figure 5) is a distinct erosional boundary that is often associated with an abrupt change in the reflection pattern, from a pronounced subparallel pattern beneath the unconformity to a less reflective pattern above, suggesting a drastic change in the depositional regime. The seismic interval velocities were found around 3.2 km/s (range of 2.3–3.7 km/s). A late Miocene age is inferred for horizon ESS3 because of a revival of tectonic activity in the Verkhoyansk-Chukotka region at about the end of the Miocene [e.g., *Khain*, 1994] and the initiation of large-scale Northern Hemisphere glaciation [e.g., *Myhre and Thiede*, 1995; *Mangerud et al.*, 1996].

3.3. Major Structural Elements

[19] To illustrate the major structural elements, a simplified, 450 km long crustal cross section (based on line BGR94-19) across the East Siberian Shelf is shown in Figure 3 together with a free-air gravity chart and the magnetic data. The seismic reflection data were depth converted using averaged interval velocities derived from stacking velocities. The locations of previously defined structural elements along the position of the line as the Blagoveshchensk Basin, the Anzhu Ridge, and the proposed southern extension of the New Siberian Basin are indicated below the section [e.g., *Kos'ko et al.*, 1993].

[20] Along that profile (Figure 3) the sedimentary unit on top of the acoustic basement, labeled ESS1, thickens gradually from ~1 km in the SSW to >6 km in the NE near the southern flank of the De Long Domain (compare Figure 4). While the surface of the acoustic basement dips gently toward the northeast in the southern half the line (distance 40–210 km), several deep-reaching listric faults in the northern half of the line, i.e., in the distance range between 220 and 450 km, displace the surface of the acoustic basement and the older sedimentary unit resting on ESS1 and bounded by unconformity ESS2. In contrast, horizon ESS3, interpreted as the base of the late Miocene through Quaternary depositional unit, is rarely affected by this faulting. The sedimentary depocenter was named by us as the East Siberian Depocenter.

[21] In the following, some selected profiles are presented in order to demonstrate the principal features in our data set in more detail. They are illustrated by interpreted seismic sections, plotted in time (Figures 6–10), which show the marker horizons ESS1, ESS2, and ESS3 and reflections in the middle and lower crust. The crust-mantle transition and undated horizons in the Cenozoic sedimentary cover are presented where well defined. The locations of the illustrated seismic sections are indicated in Figure 4.

3.4. Presentation and Discussion of Selected Lines

[22] Figure 6 shows a seismic section from line BGR94-06, south of Novaya Sibir' Island where some deep-reaching

Figure 7a. (top) Southern part of the interpreted line drawing of MCS line BGR94-19 and (bottom) example seismic section across the previously defined Blagoveshchensk Basin [*Fujita and Cook*, 1990; *Grantz et al.*, 1990c; *Kos'ko et al.*, 1993] (compare Figure 3). Along this half of the line the surface of the acoustic basement dips gently toward the north. The sedimentary succession shows an increasing thickness from 1 s twt at the SW end of the line to ~2 s twt in the NE. A deep subsided basin is not imaged in the data. The numbers indicate interval velocities in km/s. For location, see Figure 4.

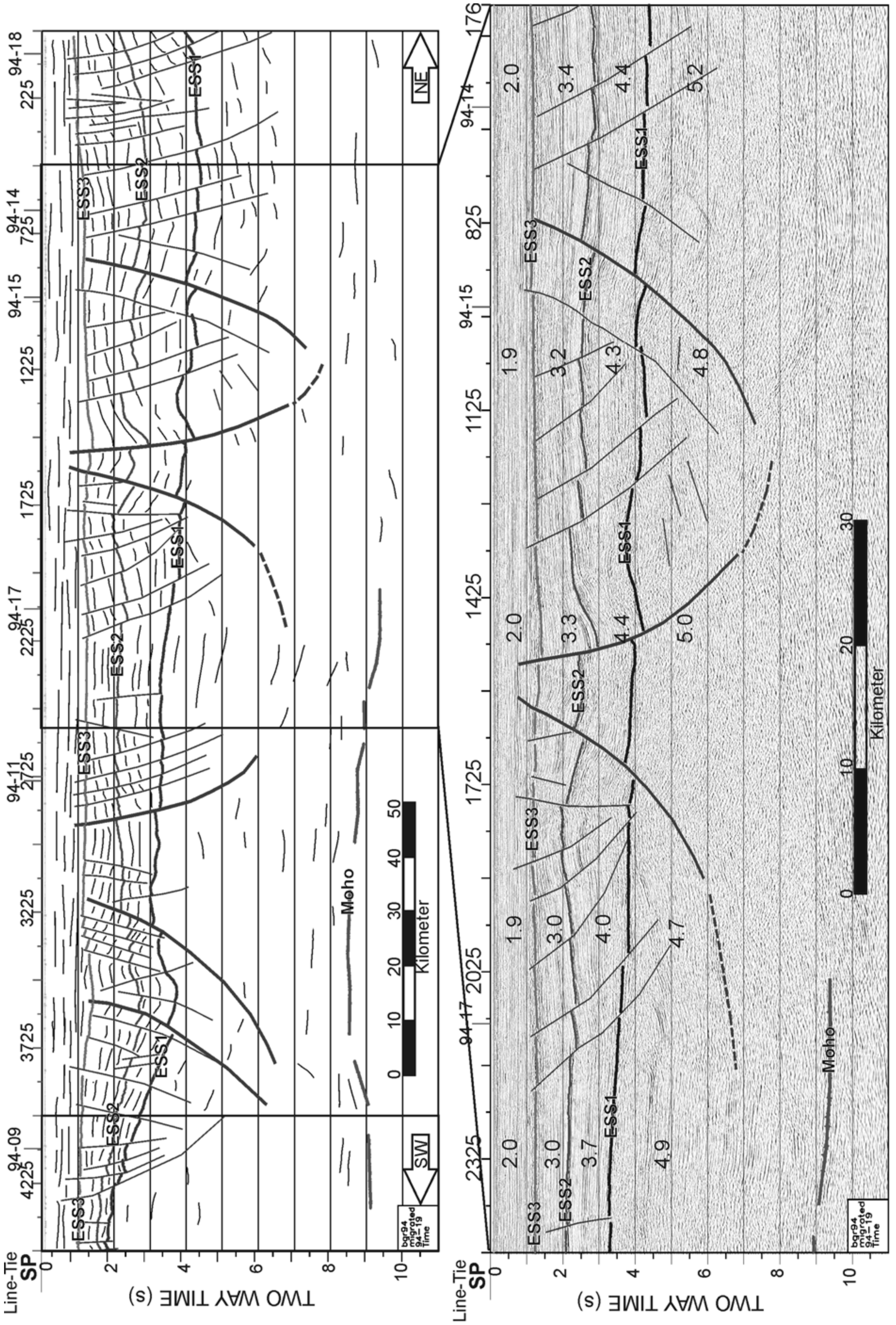
Line-Tie
SP
TWO WAY TIME (s)
0
2
4
6
8
10
94-09
4225
3725
3225
94-11
2725
94-17
2225
1725
1225
94-15
94-14
725
225
94-18
ESS1
ESS2
ESS3
Moho
Kilometer
0
10
20
30
40
50
SW
NE
bgr94 migrated 94-19 Time
2325
94-17
2025
1725
1425
1125
94-15
825
94-14
176
2.0
3.0
3.7
4.9
1.9
3.0
4.0
4.7
2.0
3.3
4.4
5.0
1.9
3.2
4.3
4.8
2.0
3.4
4.4
5.2
Kilometer
0
10
20
30

Figure 7b

listric faults are clearly imaged between shot points (SP) 150 and 1200. One of these westward dipping faults offsets horizon ESS1 for up to 300 ms between SP 900 and 950.

[23] The fault cuts also through the superimposed sediments. Other listric faults offset an east dipping highly reflective crustal unit imaged in depths of 3–4.5 s two-way travel time (twt) between SP 900 and 1200. There is no evidence for extension to the east of SP 1200. Horizon ESS1 shows a hummocky relief with peak to trough amplitudes in the range of 0.1–0.2 s twt to the east of SP 1200, and coherent reflections are lacking in upper and middle crustal levels beyond this point. Three earthquakes (*Engdahl et al.* [1998]; $m_b < 4.8$; compare Figure 4) were recorded in this region during the last 30 years. This observation is in support of our interpretation that line BGR94-06 runs across a major regional boundary that separates a rift-prone shelf region in the west from a tectonically more stable shelf region in the east, as will be discussed later.

[24] Figures 7a and 7b show the geoseismic section of line BGR94-19 traversing the Blagoveshchensk and New Siberian Basins defined by *Kos'ko* [1984] and described by *Fujita and Cook* [1990], *Grantz et al.* [1990b, 1990c], and *Kos'ko et al.* [1993] (compare Figure 3). Along that profile the well-layered sedimentary unit on top of the acoustic basement, labeled ESS1, thickens gradually from ~1 s twt in the SW to >4 s twt in the NE, near the southern flank of the De Long Domain (Figure 4). While the surface of the acoustic basement dips gently toward the northeast in the southern half the line (Figure 7a), several deep-reaching listric faults in the northern half of the line (Figure 7b), i.e., between SP 1 and 4250, displace the surface of the acoustic basement and the sedimentary unit resting on ESS1 and bounded by unconformity ESS2. In contrast, horizon ESS3, interpreted as the base of the late Miocene through Quaternary depositional unit, is rarely affected by this faulting. Apparently, the entire region traversed by line BGR94-19 is controlled mainly by subsidence increasing to the north and resembling a tilted platform. In addition, several relatively narrow (~30–50 km wide) basins with generally ESE–WNW striking axis are present, indicating that the region was affected by some sort of extension. The basins developed presumably after the formation of unconformity ESS2 but definitely prior to the formation of unconformity ESS3, i.e., between early Oligocene and late upper Miocene.

[25] The development of the ~50 km wide basin on line BGR94-15 (Figure 8) is difficult to explain by lateral extension alone. Some form of sag may have affected the basin in addition to extension along deep-reaching listric faults. Features suggesting the presence of a sag basin are also present on lines BGR94-14 and BGR94-12 (Figure 9; SP 1500–2200) but not on line BGR94-09 (compare Figure 4), indicating that its extent is limited to the northwest. The thickness of the individual basins increases from ~4 s twt at the basin shoulders to 6 s twt in the basin's center.

[26] Lines BGR97-11, BGR97-12, and BGR97-13 (Figure 10; for location, see Figure 4) are located between Novaya Sibir' Island and the De Long Islands and run across the postulated continuation of the New Siberian Basin [e.g., *Kos'ko et al.*, 1993]. The thickness of the inferred Cenozoic sedimentary cover decreases along line BGR97-11 (Figure 10, top right) from 1.8 s twt in the south to 0.5 s twt in the north with a successive northward termination by top lap of individual reflectors against the seafloor.

[27] A highly reflective band in upper crustal levels (6–8 s twt) rises toward the north while gradually fading out until it finally disappears when approaching the area of the De Long Islands. Line BGR97-12 (Figure 10, top middle) has a NE–SW orientation and runs toward the northeastern tip of Novaya Sibir' Island. The profile shows similar structural characteristics as line BGR97-11. Besides small-scale compressional and extensional faulting, no indications for the presence of a deep subsided rift basin between the De Long Uplift and Novaya Sibir' Island [e.g., *Drachev et al.*, 1999] could be detected (Figure 4). Line BGR97-13 (Figure 10, top left) runs parallel to the northern coast of Novaya Sibir' Island in a distance of ~15 nautical miles (~28 km) and thus along the central/southern flank of the postulated rift basin. A narrow half graben with a sedimentary fill of <1 s twt was observed between SP 1200 and 1500, but generally, the sedimentary cover is <0.5 s twt thick. At the southeastern end of the line a highly reflective lower crust is present in a level between 5 and 8 s twt.

[28] Along all the lines of the BGR97 survey in the Laptev Sea a seismically highly reflective lower crust was observed that is terminated below by a unit void or very poor in reflections [*Franke et al.*, 2001]. This termination was interpreted as Mohorovicic discontinuity (Moho). In contrast, the East Siberian Sea data show the Moho only occasionally (compare Figures 6–10) between 8 and 10 s twt, i.e., in at least 20–25 km assuming an average velocity of 5 km/s, which should be considered as a minimum value.

4. Discussion

4.1. Revised Tectonic Structures of the East Siberian Shelf

[29] Earlier published geological maps and structural interpretations [e.g., *Fujita and Cook*, 1990; *Kos'ko et al.*, 1993; *Drachev et al.*, 1998, 1999] assume a continuation of the rift-related New Siberian Basin from north of the Kotel'nyi-Faddeya Islands onto the shelf of the East Siberian Sea. However, our seismic data provide no support for this widely accepted assumption. Instead, the data unequivocally show that the NW trending New Siberian Basin disappears as a distinct rift basin when approaching the

Figure 7b. (top) Northern part of the interpreted line drawing of MCS line BGR94-19 and (bottom) example seismic section across the previously defined New Siberian Basin [*Fujita and Cook*, 1990; *Grantz et al.*, 1990c; *Kos'ko et al.*, 1993] (compare Figure 3). Along this part of the line several deep-reaching listric faults displace the surface of the acoustic basement and the older sedimentary unit resting on horizon ESS1. The well-layered sedimentary unit superimposing the surface of the acoustic basement thickens from ~2 s twt at the SW end of the line to >4 s twt in the NE, near the southern front of the De Long Uplift (Figure 4). The numbers indicate interval velocities in km/s. For location, see Figure 4.

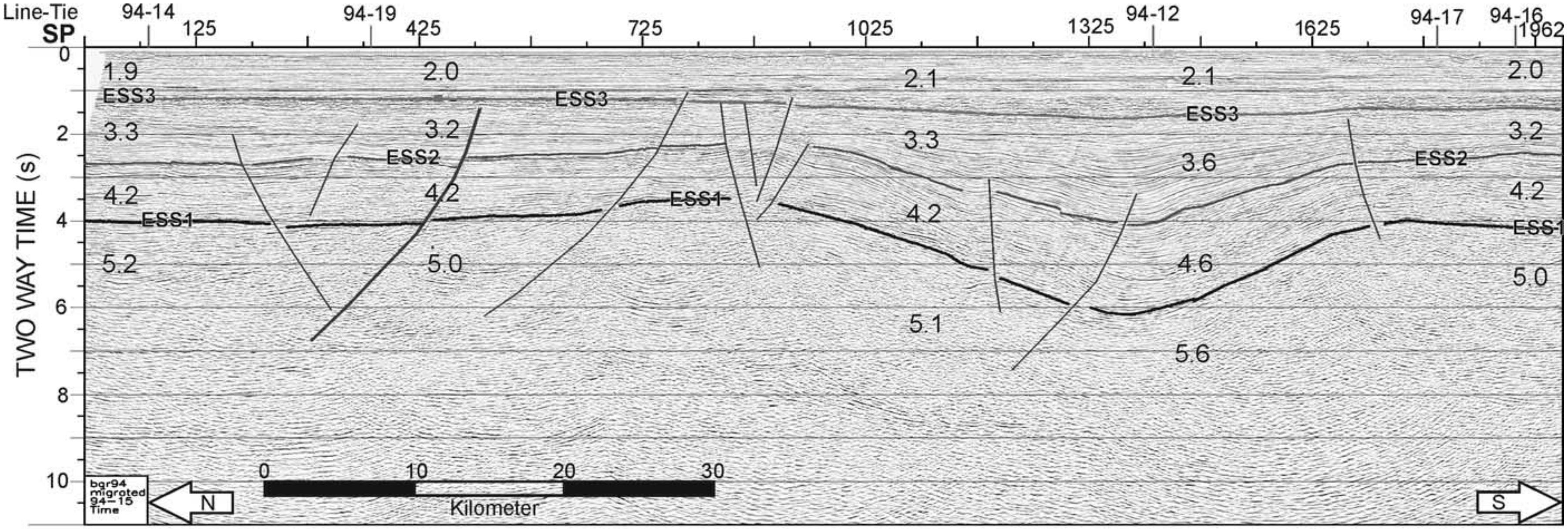

Figure 8. Interpreted seismic section of line BGR94-15 (for location, see Figure 4) showing an ~50 km wide sag-shaped basin. The thickness of the infill of the basin increases from ~4 s twt at the basin's shoulders to ~6 s twt in the center. The numbers indicate interval velocities in km/s.

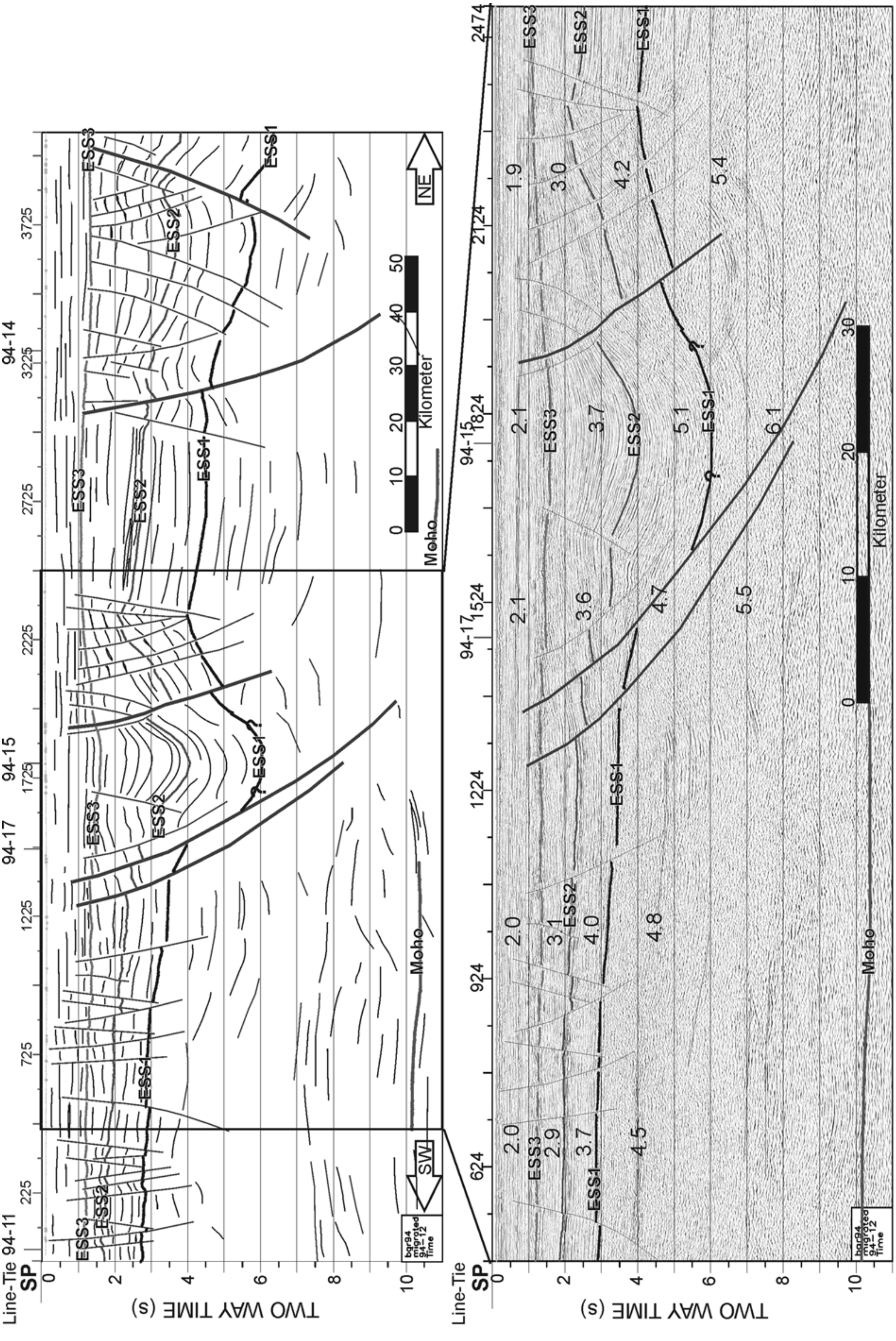
Line-Tie
SP
94-11
94-17
94-15
94-14
225
725
1225
1725
2225
2725
3225
3725
TWO WAY TIME (s)
0
2
4
6
8
10
ESS1
ESS2
ESS3
SW
NE
Moho
Kilometer
0
10
20
30
40
50
bgr94 migrated 94-12 Time
624
924
1224
1524
1824
2124
2474
2.0
2.9
3.7
4.5
3.1
4.0
4.8
2.1
3.6
4.7
5.5
3.7
5.1
6.1
1.9
3.0
4.2
5.4

Figure 9

New Siberian Islands (Faddeya Island and Novaya Sibir' Island; Figures 4 and 10).

[30] The surveyed part of the East Siberian Sea definitely does not show large Upper Cretaceous-Tertiary rift basins with the tectonic style of the Ust' Lena Rift and the Anisin Basin on the adjacent Laptev Sea shelf [*Franke et al.*, 2001] (compare Figure 11). Moreover, no indication for the Blagoveshchensk Basin, in its postulated form to stretch several hundred kilometers from south of the New Siberian Islands onto the East Siberian Shelf, could be found (compare Figures 3 and 7a) nor any indication for the so-called Anzhu Ridge postulated to form its northern boundary. In contrast to the Laptev Shelf the entire region of the East Siberian Shelf is tectonically rather quiet; no large earthquakes (magnitude > 4.5) occurred in the past 30 years in that region [*Avetisov*, 1993; *Franke et al.*, 2000].

[31] There is reasonable correlation of the seismic findings with the potential field data. The large depocenter to the south of the De Long Domain, named by us East Siberian Depocenter, correlates with both, a gravity low and a magnetic low. However, the small sag basins (top panels of Figures 7b, 8, and 9) within the East Siberian Depocenter are not well imaged in the potential field data. Figure 11 shows the width of the East Siberian Depocenter that was extended beyond our seismic data on the base of the potential field data. The extension to the west is confirmed by a line drawing interpretation of *Drachev et al.* [1999] (for location, see Figure 4, line Large89001).

[32] Our seismic data and our interpretation for the surveyed part of the East Siberian Sea shelf imply a relatively stable epicontinental platform. It is assumed to be composed of a complex suite of mainly Paleozoic and Mesozoic rocks that gradually subsided since Upper Cretaceous time with increasing rates toward the northeast (compare Figure 4) but was also affected by some form of extensional/transtensional stresses that created the relatively small ESE–WNW striking sag basins. The discovered sag basins are thought to result from a deep-seated process in the kind of "flexural cantilever model" [*Kusznir et al.*, 1987] or of "depth depending stretching" (*Roberts et al.*, 1997); that is, upper crustal extension is significantly smaller than whole crust and/or whole lithospheric extension, affecting the pre-Cenozoic crust of the East Siberian Sea shelf during the Neogene.

4.2. Tectonic Development of the East Siberian Sea in Context With the Evolution of the Arctic Ocean Basin

[33] The discovered small basins within the East Siberian Depocenter are considered to be significant tectonic features suitable to address the implication of these features for plate tectonic models concerning the evolution of the Amerasia Basin. Seafloor spreading in the Makarov Basin along an inferred N–S trending spreading axis [*Drachev et al.*, 1999] should result in E–W extension on the adjacent continental shelf as it is the case in the Laptev Sea, where the mid-oceanic Gakkel Ridge of the Eurasia Basin interacts with the Laptev continental shelf [*Franke et al.*, 2001]. The axes of the sag basins, however, show a general ESE–WNW strike orientation. Further, we miss extensional basins on the continental margin of the Makarov Basin, i.e., around and to the north of the De Long Domain. One might argue that the basaltic extrusives in the De Long Domain may mask expected rift basins. However, *Sekretov* [2001] presented three seismic reflection lines close to the shelf break that in our opinion bear only rare indications for extensional faults and rift basins. Seafloor spreading in the Makarov Basin along a possibly E–W striking spreading ridge in the Makarov Basin should create some minor compression on the adjacent continental shelf instead of extension.

[34] A key question for the adequacy of the popular rotation model for the opening of the Amerasia Basin is the existence of a major transform fault along the boundary between the Lomonosov Ridge and the Makarov Basin that is proposed to extend into the study area on the shelf of the East Siberian Basin [*Grantz et al.*, 1990a; *Embry*, 2000] (Figure 1). Although we found no conclusive evidence in our seismic data for the presence of a major northwest-southeast trending strike-slip fault/fault system, the distinct tilting of the base of the East Siberian Depocenter toward the northeast is in accordance with this hypothesis. Transtensional stress creating faults and some sort of pull-apart basins along the faults could also explain the formation of the discovered sag basins within the East Siberian Depocenter. With this scenario one would expect that the axes of the pull-apart basins, which developed along a northwest-southeast striking transform fault, have the same orientation as the transform fault. However, the axes of the discovered sag basins show an east-southeast to west-northwest strike orientation (Figure 11). Therefore our favored interpretation is that the formation of the relatively small sag basins within the East Siberian Depocenter is closely linked with the opening of the Eurasia Basin instead of with the opening of the Makarov Basin. We propose that the spreading process in the Eurasia Basin created extensional forces on the East Siberian Shelf resulting in east-west trending strike-slip or transform faults and thus the formation of pull-apart basins on the shelf of the East Siberian Sea (Figure 11). On a more global scale the basins formed because of interactions of the Eurasia plate with the North America plate. The suggested transform faults show the same general strike as the Severnyi Transfer [*Fujita et al.*, 1990; *Drachev et al.*, 1998; *Franke et al.*, 2001] (compare Figure 11). This major transform fault is believed to form the link from oceanic spreading in the Eurasian Basin to extension of continental lithosphere on the Laptev Shelf. An earthquake with a magnitude of m_b 6.0 showing a clear strike-slip mechanism (Figure 11) and a gravity low (at about 125°E, 77°N; compare Figure 2) on the Laptev Shelf marks the location of this transform fault [*Franke et al.*, 2000]. North and south of the proposed Severnyi Transfer, extensional fault plane

Figure 9. (top) Line drawing interpretation of MCS line BGR94-12 and (bottom) example seismic section showing the images of the defined seismic marker horizons ESS1, ESS2, and ESS3 (see text). Between shot points (SP) 1500 and 2200 an ~50 km wide sag-shaped basin is present in the data. The thickness of the infill of the basin increases from ~4 s twt at the basin's shoulders to ~6 s twt in the basin's center. The numbers indicate interval velocities in km/s. For location, see Figure 4.

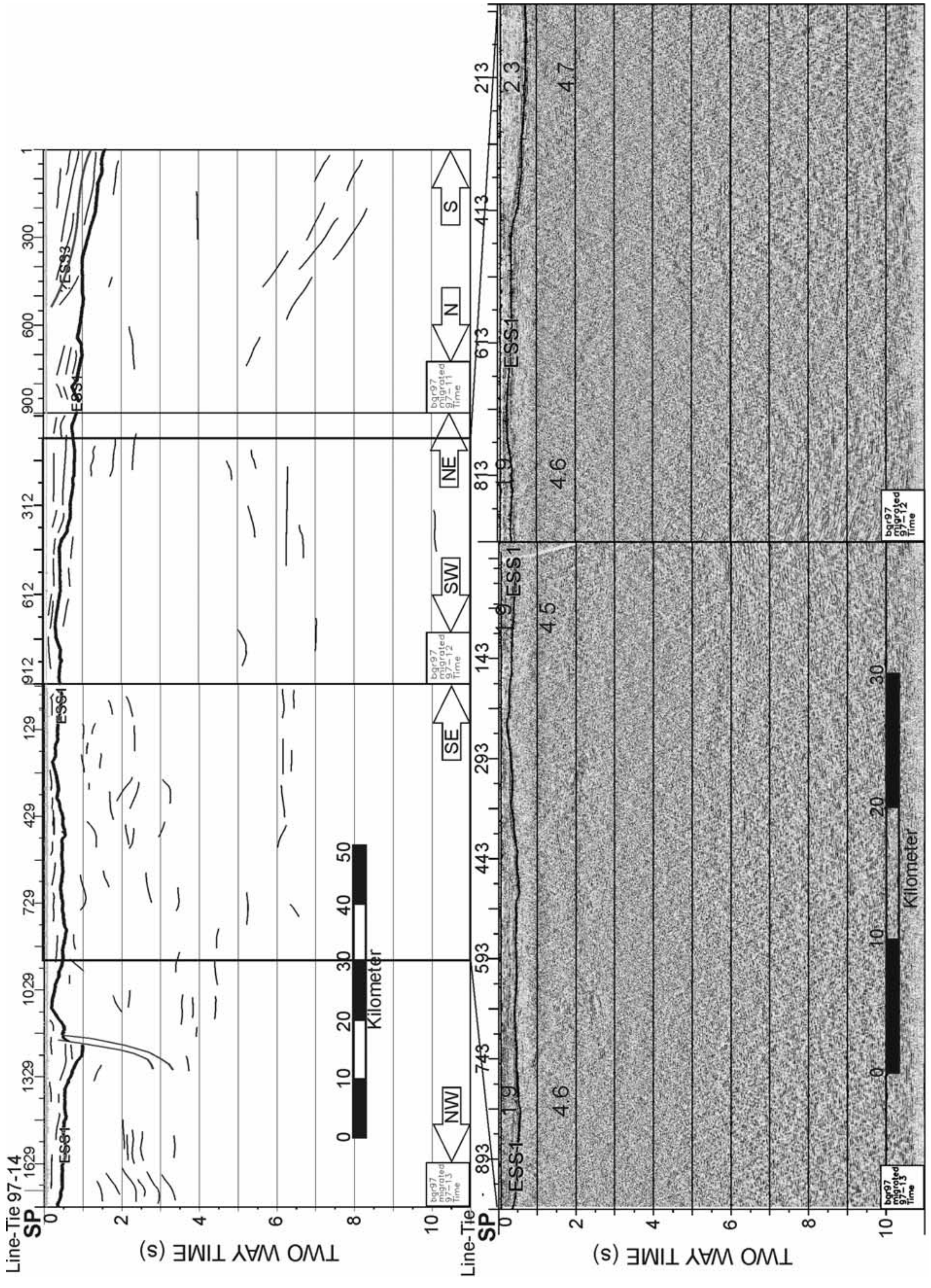
Line-Tie 97-14
SP
1629
1329
1029
729
429
129
912
612
312
900
600
300
1
ESS1
?ESS3
NW
SE
SW
NE
N
S
Kilometer
0
10
20
30
40
50
bgr97 migrated 97-13 Time
bgr97 migrated 97-12 Time
bgr97 migrated 97-11 Time
TWO WAY TIME (s)
Line-Tie
893
743
593
443
293
143
813
613
413
213
1.9
4.6
4.5
2.3
4.7

Figure 10

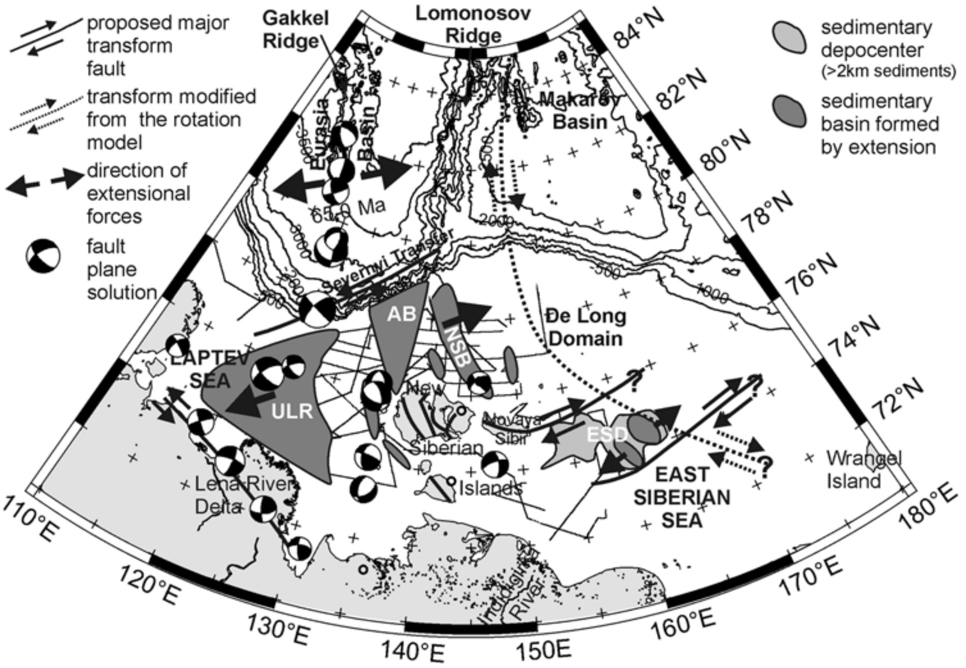

Figure 11. Basins and depocenters on the Laptev and East Siberian Shelf. The capital letters denote URL, Ust' Lena Rift; AB, Anisin Basin; NSB, New Siberian Basin; and ESD, East Siberian Depocenter. The existence of transform faults with the same general east strike as the Severnyi Transfer is proposed. The onshore extension of a major fault located on Novaya Sibir' Island and the faults located on the New Siberian Islands were adapted from *Kos'ko and Trufanov* [2002]. Apart from the event south of Novaya Sibir' Island [*Avetisov*, 1993] the focal mechanisms are from *Franke et al.* [2000]. At the intersection of the supposed east trending transform faults with the fault proposed by the rotation model the sag-shaped basins within East Siberian Depocenter may have formed. See text for a more detailed discussion.

solutions predominate. The general WSW–ENE trend of the proposed transform faults from the New Siberian Islands across the East Siberian Shelf (Figure 11) is in general agreement with a major fault located on Novaya Sibir' Island [*Kos'ko and Trufanov*, 2002], the easternmost of the New Siberian Islands (compare Figure 11), and the fault plane solution for an event south of Novaya Sibir' Island [*Avetisov*, 1993] suggests recent E–W trending strike-slip motion in this area. These assumptions are capable of explaining the basins geometry, but it is not clear why the extensional forces were transferred from the Laptev Sea to the east onto the East Siberian Shelf. A possible explanation is that the area of the basins of the East Siberian Shelf is located on an older zone of weakening that was reactivated by far-field stresses that also formed the rift basins in the Laptev Sea and resulted in seafloor spreading in the Eurasian Basin.

[35] Concerning the evolution of the wide East Siberian Depocenter, the major transform fault as predicted by the rotation model offers a scenario with a slightly adjusted location of the fault to the east as shown in Figure 11. With this configuration it is possible to explain the general dip of the relatively stable platform of the East Siberian Shelf toward the north that may be caused by dip-slip movements along this fault. The fault as shown in Figure 11 correlates with a gravity anomaly in the De Long Domain (152°E, 77.5°N to 157°E, 76°N; Figure 2, top) and contacts the location of the small basins within the East Siberian Depocenter. It might be speculated that the major transform fault as predicted by the rotation model led to the weakening of the crust at the location of the small sag basins that were finally formed in the Tertiary, i.e., between early Oligocene and late upper Miocene according to our seismic-stratigraphic concept (Figure 5) by E–W extension in connection with the opening of the Eurasia Basin.

5. Summary and Conclusions

[36] Three seismic marker horizons (ESS1, ESS2, and ESS3; Figure 5) were defined and mapped in the area of the East Siberian Sea covered by the BGR1994 and BGR1997 MCS lines. We tentatively correlate horizon ESS1 with the end of the granitoid plutonism in the Verkhoyansk-Chukotka folded system in the Late Cretaceous followed by a period of leveling. This time roughly coincides with the initial rifting processes in the Eurasia Basin. From distinct

Figure 10. (top) Line drawing interpretation of MCS lines BGR97-11, BGR97-12, and BGR97-13 and (bottom) example seismic section across the previously defined continuation of the New Siberian Basin to the southeast [e.g., *Kos'ko et al.*, 1993]. In the data, there are no indications for the presence of a deep subsided rift basin. The numbers indicate interval velocities in km/s. For location, see Figure 4.

similarities in the reflection pattern and common seismic characteristics of the sedimentary units of the shelves of the East Siberian Sea (horizons ESS2 and ESS3) and the Laptev Sea (horizons LS2 and LS3) we infer an early Oligocene age (∼33 Ma) for horizon ESS2 and late Miocene age for horizon ESS3. For the early Oligocene a regression has been documented at several localities in the east Arctic region, and a significant reorientation of relative plate motions occurred in this time in the circum-Arctic oceans. At about the end of the Miocene a revival of tectonic activity took place in the Verkhoyansk-Chukotka region, and the large-scale Northern Hemisphere glaciation was initiated.

[37] Existing geological models for the East Siberian Shelf that were mainly derived from extrapolations of the geology of the New Siberian Islands, Wrangel Island, and the northeast Siberia landmass or potential field data must be reconciled with consideration of the new available data: There is no continuation of the rift-related New Siberian Basin from north of the Kotel'nyi-Faddeya Islands onto the shelf of the East Siberian Sea. No indications for the Blagoveshchensk Basin, in its postulated form to stretch several hundred kilometers from south of the New Siberian Islands onto the East Siberian Shelf, could be found nor any indication for the so-called Anzhu Ridge.

[38] The seismic data of the surveyed part of the East Siberian Sea imply a relatively stable epicontinental platform that synsedimentarily subsided since Upper Cretaceous time with increasing rates toward the northeast (compare Figure 4) resulting in the formation of a large depocenter, named East Siberian Depocenter by us (Figure 11). Some form of extensional/transtensional stresses affected the area and created the relatively small ESE–WNW striking sag-shaped basins within the East Siberian Depocenter.

[39] The general dip of the platform of the East Siberian Shelf toward the northeast and the formation of the East Siberian Depocenter may be explained by dip-slip movements along a (slightly adjusted) major transform fault that is proposed by the rotation model for the opening of the Amerasia Basin. Although transtensional stress creating faults and some sort of pull-apart basins along the faults could also explain the formation of the discovered sag basins within the East Siberian Depocenter, the general ESE–WNW strike of these basins argues for another scenario. Our favored interpretation is that the formation of the relatively small sag basins within the East Siberian Depocenter is closely linked with the opening of the Eurasia Basin instead of with extensional forces resulting in the opening of the Makarov Basin. We found no conclusive evidence in the data from the East Siberian Shelf in favor of the opening of the Makarov Basin on either striking spreading center without the major transform fault proposed by the rotation model. We suppose that the spreading process in the Eurasia Basin created extensional forces on the East Siberian Shelf, resulting in east-west trending strike-slip or transform faults and thus the formation of relatively small pull-apart basins on the shelf of the East Siberian Sea. These basins, filled with up to 6 s twt sediments, developed primarily during Oligocene through Miocene times according to our favored seismic stratigraphy. It might be speculated that a major transform fault as predicted by the rotation model led to the weakening of the crust at the location of the small sag basins that were finally formed in the Middle Tertiary by E–W extension in connection with the opening of the Eurasia Basin.

[40] **Acknowledgments.** Several figures have been generated with the GMT software of *Wessel and Smith* [1991]. Comments by an anonymous reviewer and by W. Jokat led to substantial improvements of the manuscript. Funding of the BGR94 and BGR97 seismic surveys and this work was provided by the Federal Institute for Geosciences and Natural Resources (BGR), Hannover; Germany.

References

Alekseev, M. N., A. A. Arkhangelov, N. M. Ivanova, B. I. Kim, N. G. Patrik-Kara, I. B. Plakht, I. W. Renini, S. B. Sekretov, and C. I. Schkarubo (1992), Laptev and East Siberian seas Cenozoic, in *Paleogeographic Atlas of the Shelf Regions of Eurasia for the Mesozoic and Cenozoic*, vol. 1, pp. 14–33, Geol. Inst. Russ. Acad. of Sci., Moscow.

Avetisov, G. P. (1993), Some aspects of lithospheric dynamics of Laptev Sea, *Phys. Solid Earth, Engl. Transl.*, *29*(5), 402–412.

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

Chalmers, J. A., T. C. R. Pulvertaft, F. G. Christiansen, H. C. Larsen, K. H. Laursen, and T. G. Ottesen (1993), The southern West Greenland continental margin: Rifting history, basin development, and petroleum potential, in *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*, edited by J. R. Parker, pp. 915–931, Geol. Soc., London.

Drachev, S. S., and L. A. Savostin (1993), Ophiolites of the Bol'shoi Lyakhov Island (Novosibirsk Islands), *Geotektonika*, *6*, 33–51.

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

Drachev, S. S., G. L. Johnson, S. W. Laxon, D. C. McAdoo, and H. Kassens (1999), Main structural elements of eastern Russian Arctic continental margin derived from satellite gravity and multichannel seismic reflection data, in *Land-Ocean Systems in the Siberian Arctic: Dynamics and History*, edited by H. Kassens et al., pp. 667–692, Springer-Verlag, New York.

Embry, A. F. (2000), Counterclockwise rotation of the Arctic Alaska Plate: Best available model or untenable hypothesis for the opening of the Amerasian Basin, in *ICAM III: III. International Conference on Arctic Margins*, edited by N. W. Roland and F. Tessensohn, pp. 247–255, Alfred-Wegener Inst. for Pol. and Mar. Res., Bremerhaven, Germany.

Engdahl, R. E., R. v. d. Hilst, and R. P. Buland (1998), Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, *Bull. Seismol. Soc. Am.*, *88*, 722–743.

Franke, D., F. Krueger, and K. D. Klinge (2000), Tectonics of the Laptev Sea-Moma 'Rift' region: Investigation with seismologic broadband data, *J. Seismol.*, *4*, 99–116.

Franke, D., K. Hinz, and O. Oncken (2001), The Laptev Sea Rift, *Mar. Pet. Geol.*, *18*(10), 1083–1127.

Fujita, K., and D. B. Cook (1990), The arctic continental margin of eastern Siberia, in *The Geology of North America*, vol. L, *The Arctic Ocean Region*, edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 289–304, Geol. Soc. of Am., Boulder, Colo.

Fujita, K., and J. T. Newberry (1982), Tectonic evolution of northeastern Siberia and adjacent regions, *Tectonophysics*, *89*, 337–357.

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

Grantz, A., S. D. May, P. T. Taylor, and L. A. Lawver (1990a), Canada Basin, in *The Geology of North America*, vol. L, *The Arctic Ocean Region*, edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 379–402, Geol. Soc. of Am., Boulder, Colo.

Grantz, A., S. D. May, and P. E. Hart (1990b), Geology of the Arctic Continental Margin of Alaska, in *The Geology of North America*, vol. L, *The Arctic Ocean Region*, edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 257–288, Geol. Soc. of Am., Boulder, Colo.

Grantz, A., A. R. Green, D. G. Smith, J. C. Lahr, and K. Fujita (1990c), Major Phanerozoic tectonic features of the Arctic Ocean region, in *The Geology of North America*, vol. L, *The Arctic Ocean Region*, edited by A. Grantz, L. Johnson, and J. F. Sweeney, Plate 11, Geol. Soc. of Am., Boulder, Colo.

Gronlie, G. (1977), Preliminary results of seismic velocity measurements in Spitsbergen, in *Norsk Polarinstitt Arbok 1977*, reprint, pp. 229–236, Universitetsforlaget, Oslo, Norway.

Haq, B. U., J. Hardenbrol, and P. R. Vail (1988), Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, in *Sea-Level*

Changes—An Integrated Approach, edited by C. K. Wilgus et al., *SEPM Spec. Publ.*, *42*, 71–108.

Hinz, K., and H. U. Schlüter (1980), Continental margin off East Greenland, in *Proceedings of the 10th World Petroleum Congress*, vol. 2, pp. 405–418, Heyden, Philadelphia, Pa.

Hinz, K., O. Eldholm, M. Block, and J. Skogseid (1993), Evolution of the North Atlantic volcanic margins, in *Petroleum Geology of Northwest Europe*, *Proceedings of the 4th Conference*, edited by J. R. Parker, pp. 901–913, Geol. Soc., London.

Hinz, K., G. Delisle, B. Cramer, D. Franke, U. Fiegut, F. Lindemann, S. Neben, H. Tostmann, and M. Zeibig (1998), Cruise report, marine seismic measurements and geoscientific studies on the shelf and slope of the Laptev Sea and East Siberian Sea/Arctic with M. V. Akademik Lazarev, IB. Kapitan Dranitsin, 23 August–8 October, 1997. Part II: Preliminary scientific results, *BGR Rep. 116693*, 160 pp., Bundesanst. für Geowis. und Rohstoffe, Hannover, Germany.

Jackson, H. R., and K. Gunnarsson (1990), Reconstructions of the Arctic: Mesozoic to Present, *Tectonophysics*, *172*, 303–322.

Khain, V. E. (1994), *Geology of Northern Eurasia (Ex USSR)*, vol. 2, *Phanerozoic Fold Belts and Young Platforms*, 404 pp., Bornträger, Berlin.

Kos'ko, M. K. (1984), East Siberian Sea, in *Seas of the Soviet Arctic*, vol. 9, *Geologic Structure of USSR and Its Relationship to the Distribution of Mineral Resources*, edited by I. S. Gramberg and Y. E. Pogrebitsky, pp. 51–60, Nedra, St. Petersburg, Russia.

Kos'ko, M. K., and G. V. Trufanov (2002), Middle Cretaceous to Eopleistocene sequences on the New Siberian Islands: An approach to interpret offshore seismic, *Mar. Pet. Geol.*, *19*, 901–919.

Kos'ko, M. K., B. G. Lopatin, and V. G. Ganelin (1990), Major geological features of the islands of the East Siberian and Chukchi Seas and the northern coast of Chukotka, *Mar. Geol.*, *93*, 349–367.

Kos'ko, M. K., M. P. Cecile, J. C. Harrison, V. G. Ganelin, N. V. Khadoshko, and B. G. Lopatin (1993), Geology of Wrangel Island between Chukchi and East Siberian Seas, northeastern Russia, *Geol. Surv. Can. Bull.*, *461*, 101 pp.

Kristoffersen, Y. (1990), Eurasia Basin, in *The Geology of North America*, vol. L, *The Arctic Ocean Region,* edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 365–378, Geol. Soc. of Am., Boulder, Colo.

Kusznir, N. J., G. D. Karner, and S. Egan (1987), Geometric, thermal and isostatic consequences of detachments in continental lithosphere extension and basin formation, in *Sedimentary Basins and Basin Forming Mechanisms*, edited by C. Beaumont and A. J. Tankard, *Mem. Can. Soc. Pet. Geol.*, *12*, 185–203.

Lane, L. S. (1997), Arctic Ocean: Evidence against a rotational origin, *Tectonics*, *16*(3), 363–387.

Lawver, L. A., and C. R. Scotese (1990), A review of tectonic models for the evolution of the Canada Basin, in *The Geology of North America*, vol. L, *The Arctic Ocean Region*, edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 593–618, Geol. Soc. of Am., Boulder, Colo.

Laxon, S., and D. McAdoo (1994), Arctic Ocean gravity field derived from ERS-1 satellite altimetry, *Science*, *165*, 621–624.

Mangerud, J., E. Jansen, and J. Y. Landvik (1996), Late Cenozoic history of the Scandinavian and Barents ice sheets, *Global Planet. Change*, *12*, 11–26.

Myhre, A. M., and J. Thiede (1995), *North Atlantic-Arctic Gateways*, *Proceedings of the Ocean Drilling Program, Initial Reports*, vol. 151, 926 pp., Ocean Drill. Program, College Station, Tex.

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

Parfenov, L. M., L. M. Natopov, S. D. Sokolov, and N. V. Tsukanov (1993), Terrane analysis and accretion in north-east Asia, *Island Arc*, *2*, 35–54.

Roberts, A. M., E. R. Lundin, and N. J. Kusznir (1997), Subsidence of the Voring Basin and the influence of the Atlantic continental margin, *J. Geol. Soc. London*, *154*, 551–557.

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

Savostin, L. A., L. M. Natapov, and A. P. Stavsky (1984), Mesozoic paleogeodynamics and paleogeography of the Arctic region, in *Arctic Geology Reports*, vol. 4, *27th International Geological Congress*, pp. 217–237, Nauka, Moscow.

Sekretov, S. B. (2001), Northwestern margin of the East Siberian Sea, Russian Arctic: Seismic stratigraphy, structure of the sedimentary cover and some remarks on the tectonic history, *Tectonophysics*, *339*, 353–383.

Srivastava, S. P., and C. Tapscott (1986), Plate kinematics of the North Atlantic, in *The Geology of North America*, vol. M, *The Western Atlantic Region (A Decade of North American Geology)*, edited by B. E. Tucholke and P. R. Vogt, pp. 379–404, Geol. Soc. of Am., Boulder, Colo.

Taylor, P. T., L. C. Kovacs, P. R. Vogt, and G. L. Johnson (1981), Detailed aeromagnetic investigation of the Arctic Basin: 2, *J. Geophys. Res.*, *86*, 6323–6333.

Verhoef, J., R. Roest, R. Macnab, and J. Arkani-Hamad (1996), Magnetic anomalies of the Arctic and North Atlantic Oceans and adjacent land areas, *Open File Rep. 3125a*. Geol. Surv. of Can., Ottawa.

Vogt, P. R., P. T. Taylor, L. C. Kovacs, and G. L. Johnson (1979), Detailed aeromagnetic investigation of the Arctic Basin, *J. Geophys. Res.*, *84*, 1071–1089.

Vogt, P. R., L. C. Kovacs, C. Bernero, and S. P. Srivastava (1982), Asymmetric geophysical signatures in the Greenland-Norwegian and southern Labrador seas and the Eurasian Basin, *Tectonophysics*, *89*, 95–160.

Weber, J. R., and J. F. Sweeney (1990), Ridges and basins in the Arctic Ocean, in *The Geology of North America*, vol. L, *The Arctic Ocean Region*, edited by A. Grantz, L. Johnson, and J. F. Sweeney, pp. 305–336, Geol. Soc. of Am., Boulder, Colo.

Wessel, P., and W. Smith (1991), Free software helps map and display data, *Eos Trans. AGU*, *72*, 441, 445–446.

Zonenshain, L. P., M. I. Kuzmin, and L. M. Natapov (1990), *Geology of the USSR: A Plate Tectonic Synthesis*, *Geodyn. Ser.*, vol. 21, AGU, Washington, D. C.

D. Franke, K. Hinz, and C. Reichert, Federal Institute for Geosciences and Natural Resources, B3.16, Stilleweg 2, D-30655 Hannover, Germany. (dieter.franke@bgr.de; karl.hinz@bgr.de; christian.reichert@bgr.de)

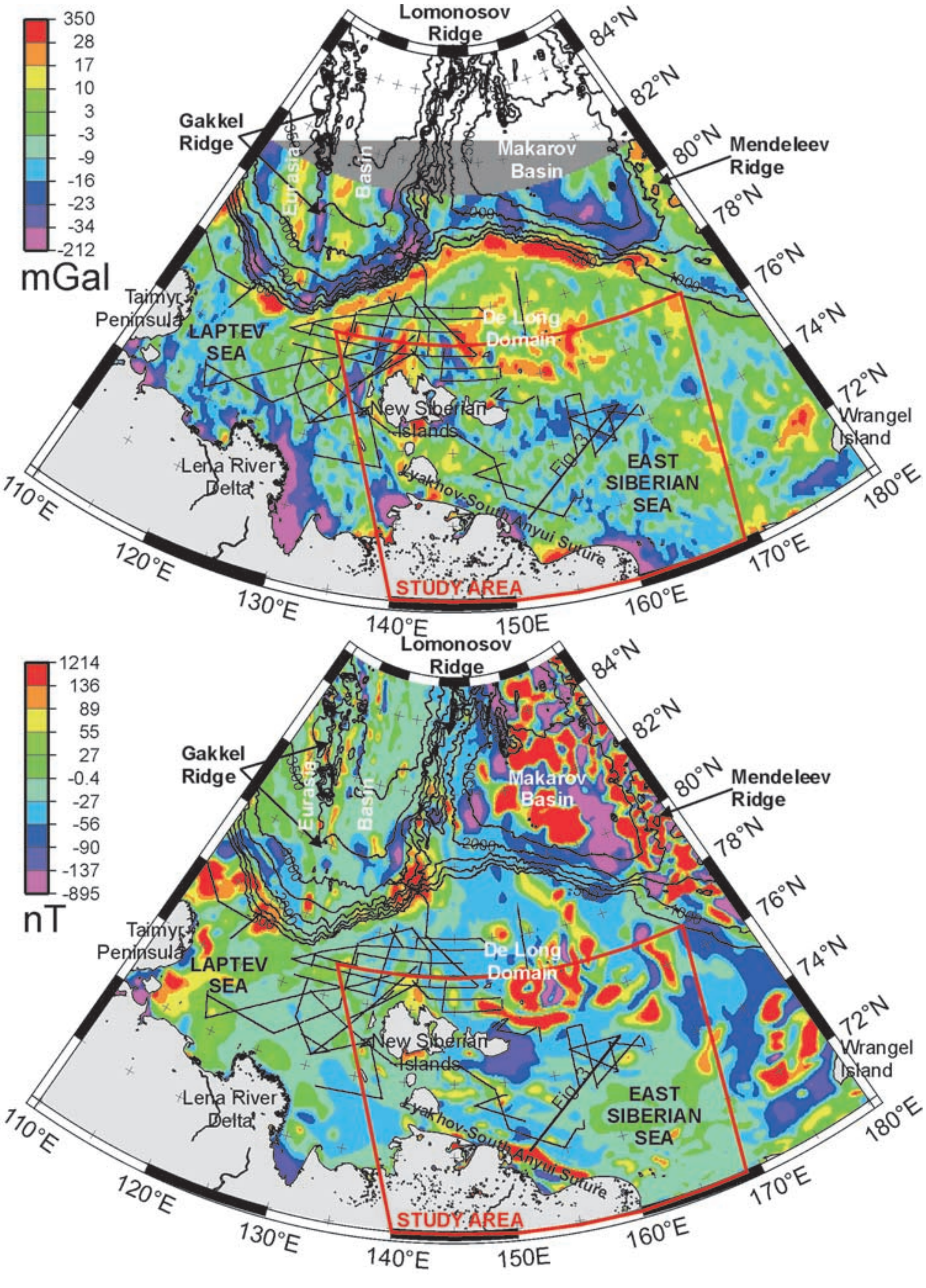

Figure 2. (top) Altimeter-derived marine gravity field to latitude of 82°N [*Laxon and McAdoo*, 1994] and (bottom) airborne magnetic data [*Verhoef et al.*, 1996]. The main structural elements of the eastern Russian Arctic are marked. The area under study and BGR's multichannel reflection seismic (MCS) lines are indicated.