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Evolution of the West Siberian Basin

A.V. Vyssotski[a,*], V.N. Vyssotski[b], A.A. Nezhdanov[c]

[a]Chevron, 1500 Louisiana Street, Houston, TX 77002 USA
[b]TNK-BP, 1 Arbat St, Moscow 119019, Russian Federation
[c]OOO TyumenNIIgiprogas, 2 Vorovskogo Str., Tyumen 625019, Russin Federation

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Abstract

The West Siberian Basin is one of the largest intra-cratonic basins of the world and an important hydrocarbon province of Russia. Perhaps the most important geologic event in Siberia was the emplacement of basalts around ~250 Ma (i.e. Permo-Triassic boundary) covering an area of about 5×10^6 km^2. This volcanism may be responsible for a mass extinction that occurred around Permian-Triassic time. The pre-basaltic rifting event was limited to the north-northeastern sector of the basin. Initial basin wide subsidence took place in the Jurassic as a result of which the western part of Siberia became the West Siberian Basin bounded by uplifts to the east and to the west. One of the surprising aspects of the West Siberian Basin is the abundance of sub-vertical faults believed to be result of strike-slip movement. While intra-plate inversions and fault reactivation structures have been observed in many cratons, sub-vertical faults observed in the West Siberian Basin are unique because of their geometries and abundance. The differentiation between the effects of tectonics and eustasy in cratonic basins is simple—the global eustatic signal is basin-wide with regional and local tectonics playing an overprinting role. Thus, the Middle Jurassic–Turonian 1st, 2nd, and 3rd order cycles in the West Siberian Basin were primarily driven by eustasy. The Middle Jurassic–Turonian series can be subdivided into two second-order and 16 third-order transgressive–regressive cycles (within dataset extent). Fourth-order cycles appear to be controlled by delta shifting. Although extensively studied, a number of fundamental questions regarding the origin and evolution of the West Siberian Basin remain unresolved or poorly documented in the literature.

Keywords: West Siberian Basin; Structural evolution; Sequence stratigraphy; Rifts; Flood basalts; Grabens; Siberian platform; Petroleum geology

1. Introduction

The West Siberian Basin is one of the largest intra cratonic basins of the world (Fig. 1), covering an area of 3.5 million km^2 (1.3 million mi^2). The Basin is unique, as it has no credible modern analog. It is outlined by the Novaya–Zemlya and the Ural Mountains to the west, the Turgay trough to the southwest, the Kazakh highlands to the south, the Altay–Sayan uplift to the southeast, the East Siberian platform to the east, and the late Paleozoic to Mesozoic Taymir folded belt and the Yenisey–Khatanga trough to the northeast (Fig. 1). The basin is opened to the Kara and Barents seas to the north.

The West Siberian Basin is a huge Mesozoic–Cenozoic sedimentary depocenter. Like other intracratonic basins, the history of its development is complex and poorly understood. The basement of the West Siberian Basin consists of peneplaned folded and metamorphosed orogenic systems and platformal blocks (Peterson and Clarke, 1991; Surkov and Zhero, 1981; Kontorovich et al., 1975). The formation of the basement was completed during the Permian as part of the Pangea super-continent assemblage (Ziegler, 1989; Sengor and Natal'in, 1996). Fig. 2 provides an overview of the stratigraphy of the West Siberian Basin which will be discussed below.

Initial exploration for oil and gas in the West Siberian Basin began in 1948. Interest in the West Siberian Basin increased dramatically after commercial oil and gas discoveries in the 1960s. The first commercial oil discovery was made in 1961 in the lower Cretaceous reservoir of

* Corresponding author. Tel.: +1 713 628 1238; fax: +1 713 432 6675.
E-mail address: alexeivyssotski@chevrontexaco.com (A.V. Vyssotski).

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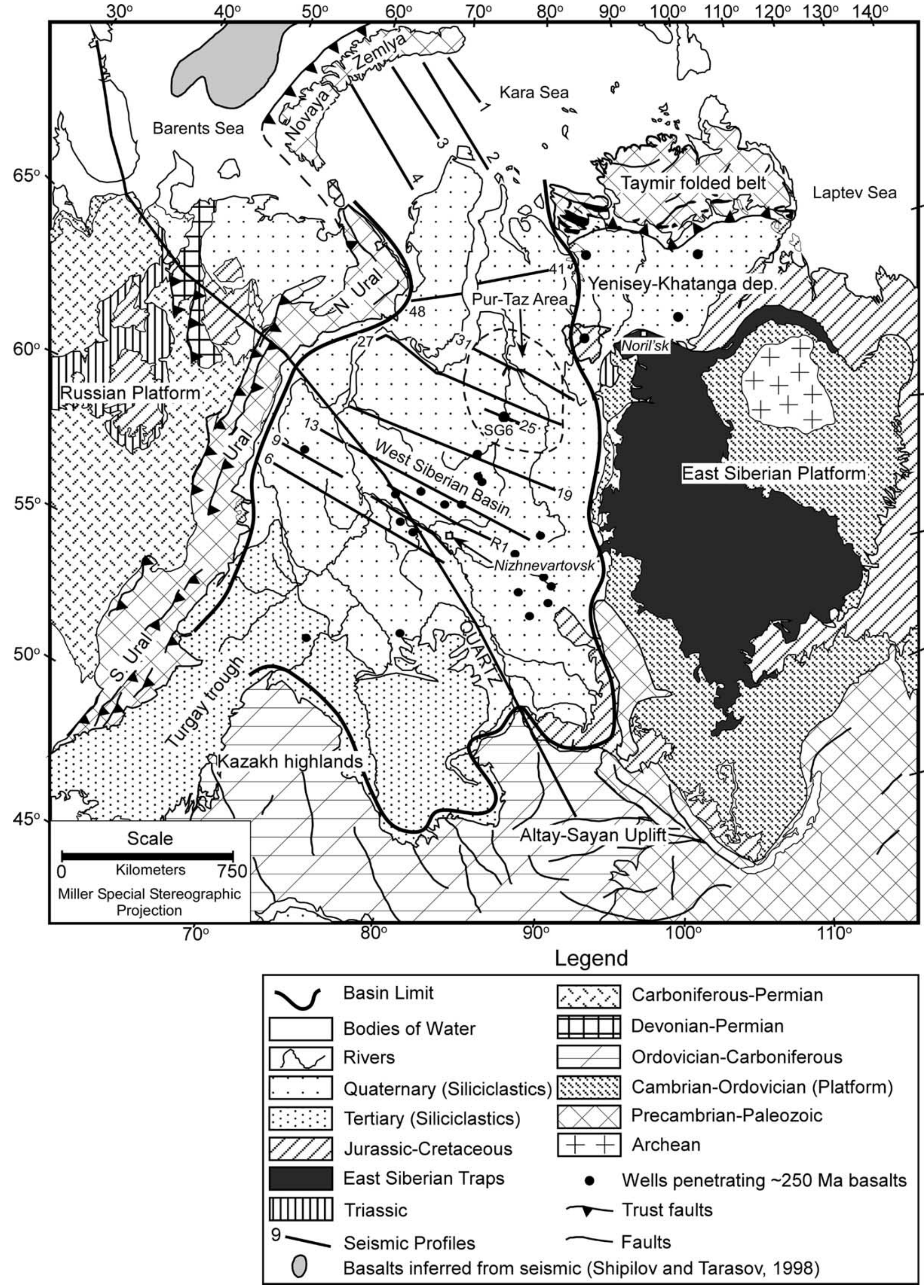

Fig. 1. Simplified geologic map of the West Siberian Basin and surrounding areas. Major tectonic features limiting basin are labeled. Locations of seismic profiles and key wells referenced in this work are shown. Base map is re-drawing and greatly simplified from Choubert and Faure-Muret, 1976.

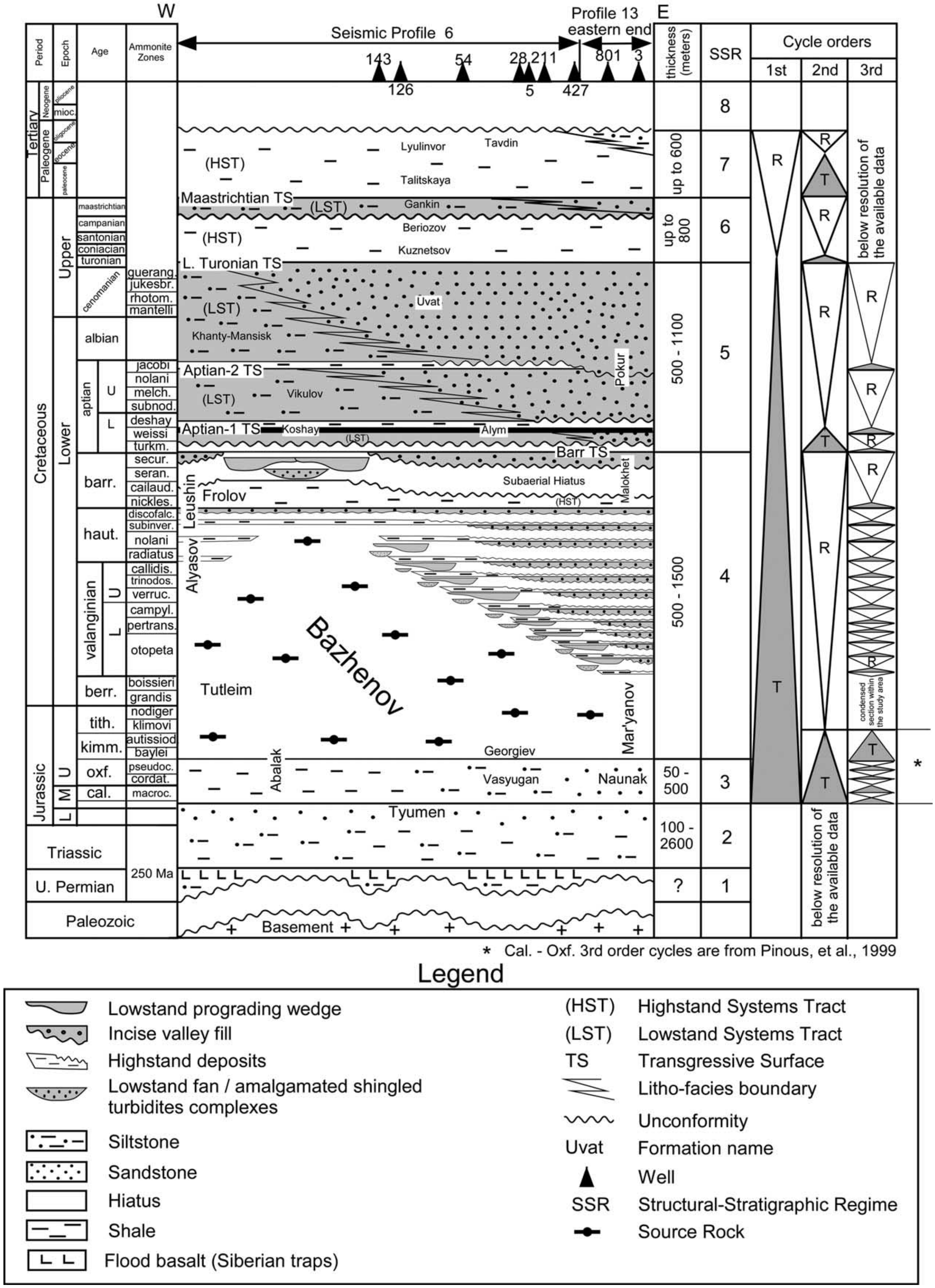

Fig. 2. Summary of the West Siberian Basin chronostratigraphy, structural-stratigraphic regimes (SSR) and cyclicity (modified after Vyssotski, 2001).

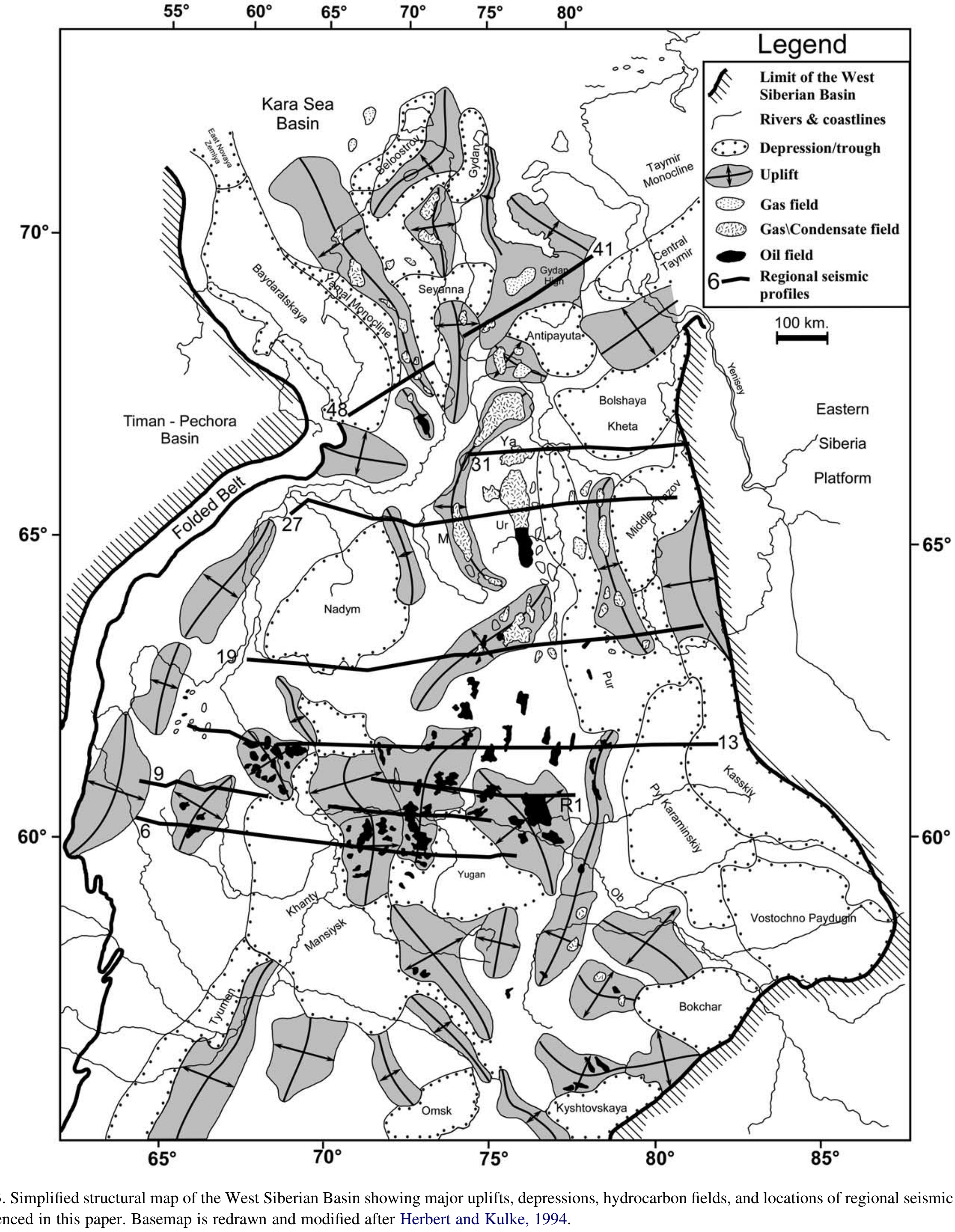

Fig. 3. Simplified structural map of the West Siberian Basin showing major uplifts, depressions, hydrocarbon fields, and locations of regional seismic profiles referenced in this paper. Basemap is redrawn and modified after Herbert and Kulke, 1994.

the Megion field (located south of Nizhnevartovsk, see Fig. 1). The first commercial gas discovery was made in 1962 in the Upper Cretaceous deposits of the Megion Field (Kontorovich et al., 1975). Currently more than 600 oil and gas fields have been discovered in the Basin (Fig. 3). Oil fields dominate the central and southern parts of the basin, whereas gas fields are common to the north. This hydrocarbon distribution is explained by increasing thermal maturity of the hydrocarbon source rocks from south to north. The primary source rock (Bazhenov formation) is in the oil generation window in the central and southern parts of the basin, and in the gas generation window in the northern part of the basin.

The West Siberian Basin is the major hydrocarbon province of Russia. According to an unofficial estimate, its expected original oil and condensate in place is greater than 1300 billion barrels (188 billion tones), and gas in place is over 4000 trillion cubic feet (115 TCM). Most of the hydrocarbons are being produced from structural traps involving Cretaceous siliciclastic reservoirs. Production potential of the West Siberian Basin is tremendous. Cumulative basin oil production is over 60 billion barrels, and gas production is over 400 TCF. During 1985–1990, the West Siberian Basin was producing ∼13% of the world's oil; during 1990s its production dropped to ∼5% as a result of political reforms; in 2004 the production increased to ∼7% of the world's oil.

2. Crust and lithosphere

Early studies of the continental crust underlying the West Siberian Basin were conducted using gravity data (Borisov, 1967; Demenitskaya, 1961; Fotiadi et al., 1969; Kontorovich et al., 1975; Surkov and Zhero, 1981). More recent studies have utilized deep seismic sounding profiles to evaluate the thickness and geometry of the continental crust and uppermost mantle (Morozova et al., 1999; Morozov et al., 1998; Egorkin, 1991; Kovylin, 1985; Kontorovich et al., 1975). This paper references only one long-range seismic profile—QUARTZ (Fig. 1). The authors have elected to use the 3850 km long QUARTZ profile because it is 'one of the best-quality and best-studied ultra-long range profiles of the Russian Deep Seismic Sounding program' (Morozov, 1998). This profile has been recently reprocessed, modeled and made readily available to the research community (Morozova et al., 1999; Morozov et al., 1998).

In general, results of all these studies agree and show that depth to Moho gradually decreases from 50 km beneath areas surrounding the West Siberian Basin (i.e. the Urals, Altay–Sayan fold belt and East Siberian Platform) to 38 km beneath the center of the basin (Figs. 4 and 5(A)). Depth to the M-discontinuity underlying the adjacent East Siberian Platform varies from 35 km (northwest) to 50 km to the west (Kravchenko and Shakhot'ko, 1995).

Some inconsistency is observed between lithosphere thicknesses reported by various authors. For example, Artemieva and Mooney (2001) describe thinner lithosphere beneath the West Siberian Basin and thicker lithosphere in areas surrounding the basin; whereas Morozova et al. (1999) show that lithosphere beneath the West Siberian Basin is thicker than that beneath Altay (Fig. 5(B) and (C)).

3. Paleozoic basement

The basement of the West Siberian Basin formed as a result of the Upper Paleozoic collision between the Russian Platform, the East Siberian Platform, and Kipchak Arc complex (Sengor and Natal'in, 1996; Fig. 6). In general the Paleozoic basement under the West Siberian Basin was peneplaned during the Permian-Triassic time. One of the most prominent products of the Upper Paleozoic collision are the Ural Mountains, which extend from Novaya Zemlya to the Aral sea (Fig. 1). The collision that formed the Urals started in the south during the late Visean–Sepukhovian times, reached the N. Urals in the Late Carboniferous and Novaya Zemlya in the Early Permian (e.g. Fokin et al., 2001; Nikishin et al., 1996). It is important to note that timing of this collision is a subject of controversy. The Urals are considered to be a key in understanding of Paleozoic plate tectonics, because with exception of a Quaternary uplift, the Urals remained undeformed since the terminal collision. Information on origin and evolution of the Urals can be found in following publications: Matte, 1995, 2002; Alvarez-Marron et al., 2000; Ayarza et al., 2000; Brown et al., 1999; Chemenda et al., 1997.

4. Tectonic evolution and stratigraphy

The evolution of the West Siberian Basin is characterized by graben formation (northeast area and Kara Sea), siliciclastic deposition, basin-wide subsidence, relative uplift of the basin margins, development of localized uplifts and depressions, and strike-slip deformation that produced sub-vertical faults. The geometry of the basin is best illustrated by line-drawings of the selected regional seismic profiles (Figs. 7–9). The location of these sections is shown on Figs. 1, 3, 4, 11, 14, 17 and 18. A cursory inspection of Figs. 7–9 indicates that sequence stratigraphic methods can be applied with confidence only to the Middle Jurassic–Turonian section. For the early history of the West Siberian Basin, the authors rely on the presence of a widespread basaltic layer that separates a pre-volcanic sequence (SSR1) from the post-volcanic, pre-Middle Jurassic sequence (SSR2) (see Fig. 2).

Eight structural-stratigraphic regimes (SSR) are observed overlying the basement (see Fig. 2):

SSR1: ∼250 Ma flood basalt event (Tunguska basalts) capping Permian continental deposits (basin-wide) and rift sequence (north-northeast only).
SSR2: Triassic–Middle Jurassic continental and lacustrine deposits.
SSR3: the Callovian–Oxfordian T/R cycle (marine and continental deposits).
SSR4: the Upper Jurassic–Barremian T/R cycles (marine and continental deposits).

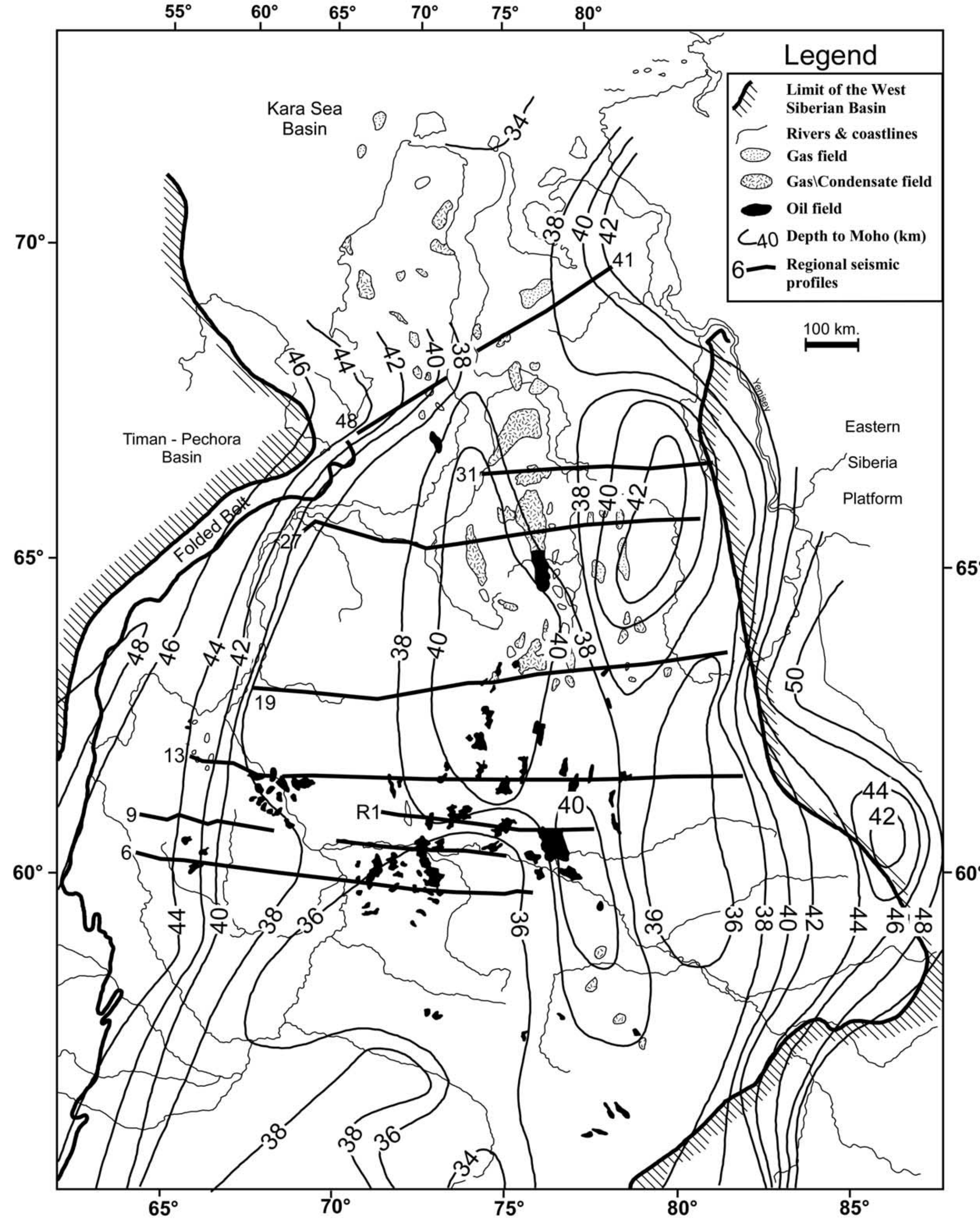

Fig. 4. West Siberian Basin depth of Moho map (contour lines are in kilometers). Location of oil/gas fields and seismic profiles is shown for reference. Depth to Moho map is modified after Kovylin, 1985.

SSR5: the Aptian–Cenomanian T/R cycles (marine and continental deposits).
SSR6: the Turonian–Maastrichtian T/R cycle (marine and continental deposits).
SSR7: the Maastrichtian–Eocene T/R cycle (marine and continental deposits).
SSR8: Oligocene to the recent mega-sequence (continental and lacustrine deposits).

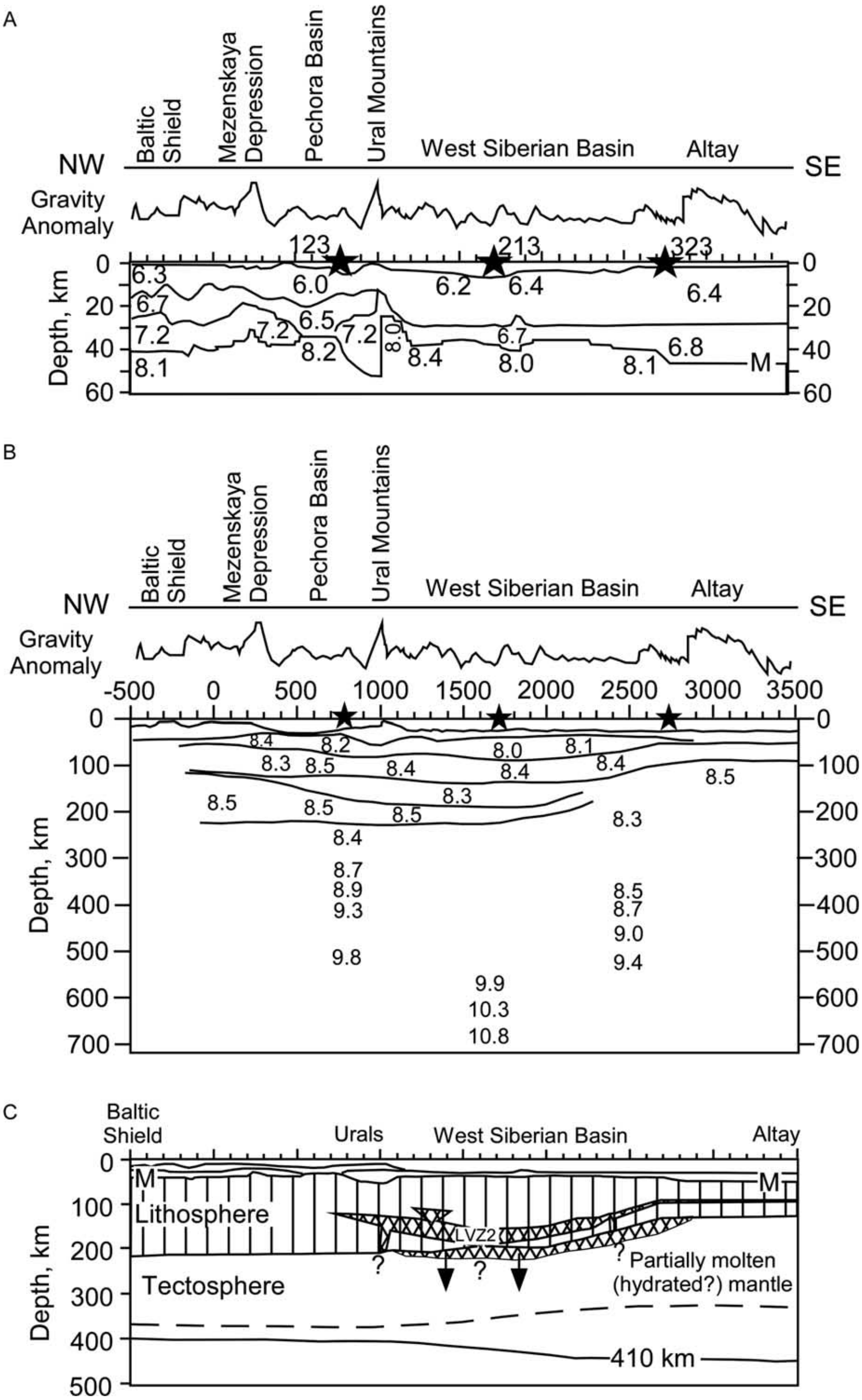

Fig. 5. (A) The diagram shows crustal velocity-interface structure along the profile QUARTZ. Velocities are measured in kilometers per second. Stars mark location of nuclear explosions. Free air gravity anomaly is shown above the cross section. (B) The uppermost mantle velocity-interface structure along the QUARTZ profile. (C) An interpretation of the lithospheric structure along QUARTZ profile. Presence of shallow low velocity zone 2 (LVZ2) underlaying West Siberian Basin may suggest mechanical instability (figures A, B and C were excerpted and modified with permission from Morozova et al., (1999)).

4.1. Pre-Triassic basin evolution

4.1.1. Remarks concerning the distribution of basalts equivalent to the Tunguska volcanics (top of SSR1)

Perhaps the single most important event in the geology of Siberia was the emplacement of Siberian flood basalts around ~250 Ma, i.e. the Permo-Triassic boundary. Basalts were emplaced in a vast spatial distribution over a period of about one million years, and are not limited to grabens observed in the north-northeast portion of the basin. Available data and literature reviews advocate that basalts cover the East Siberian Platform, West Siberian Basin,

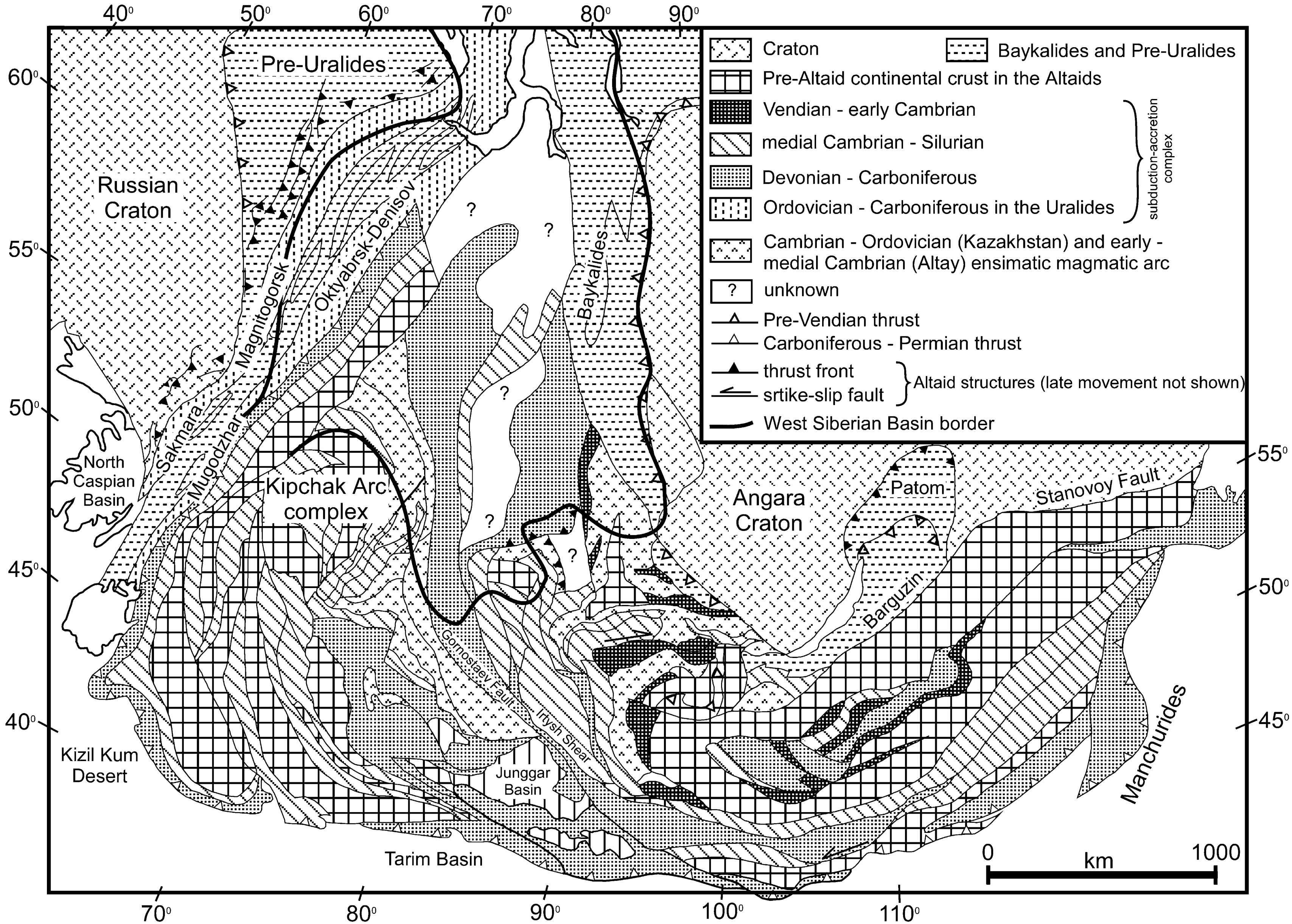

Fig. 6. Generalized tectonic map of the Altaids and related surrounding units (excerpted and modified with permission from Sengor and Natal'in, (1996). (© 1996 Cambridge University Press)

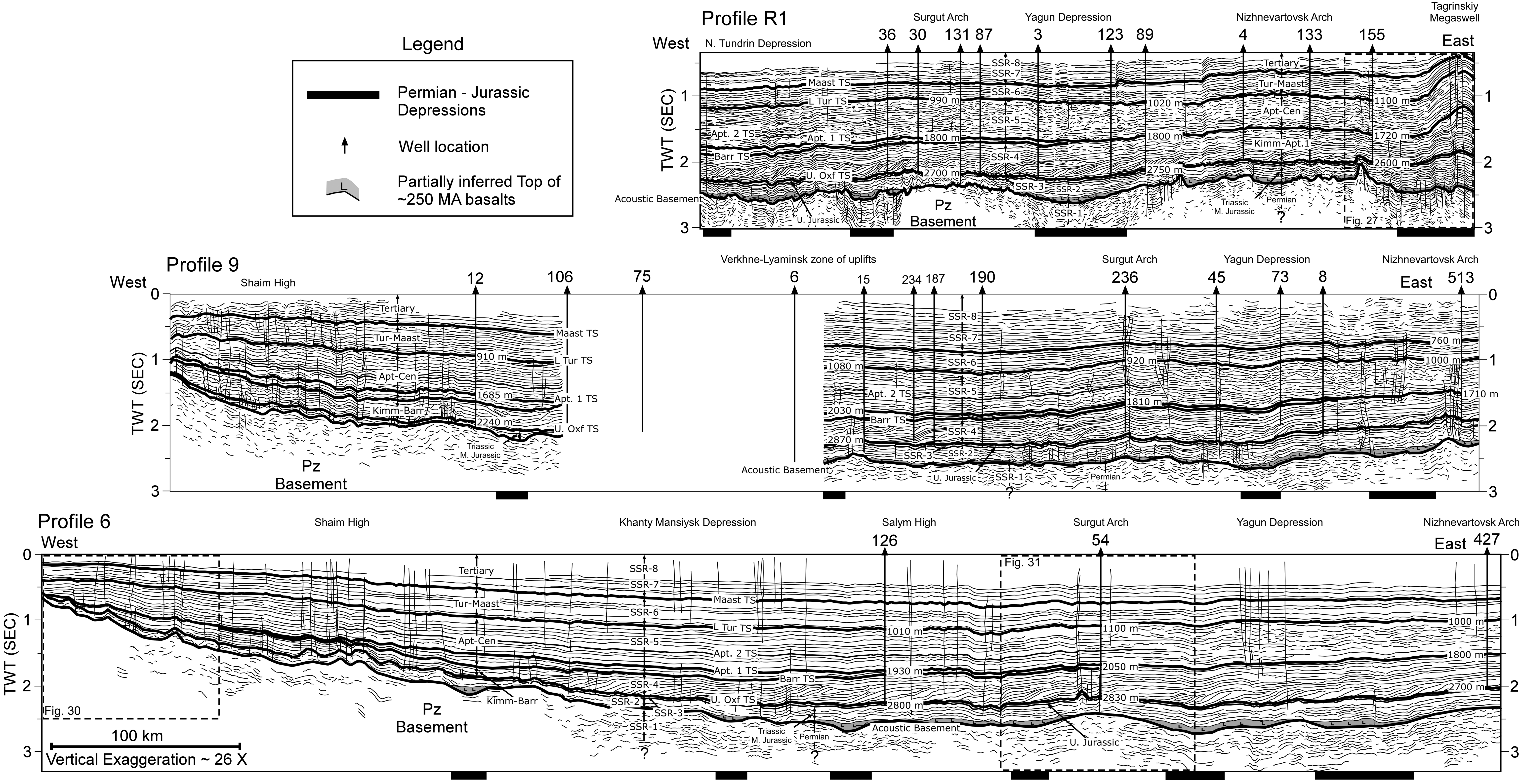

Fig. 7. Line drawing of the regional seismic profiles 6, 9, and R1.

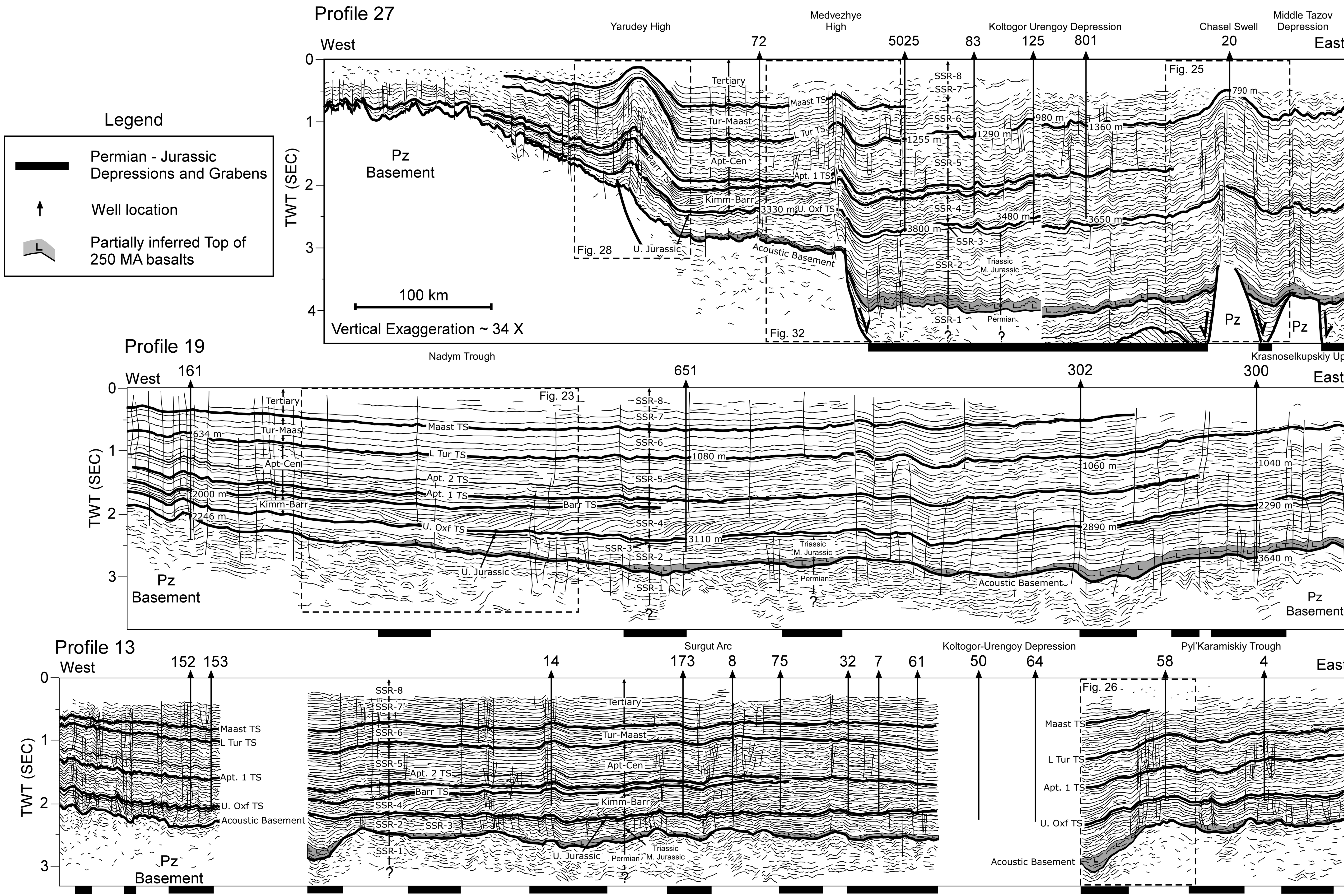

Fig. 8. Line drawing of the regional seismic profiles 13, 19, and 27.

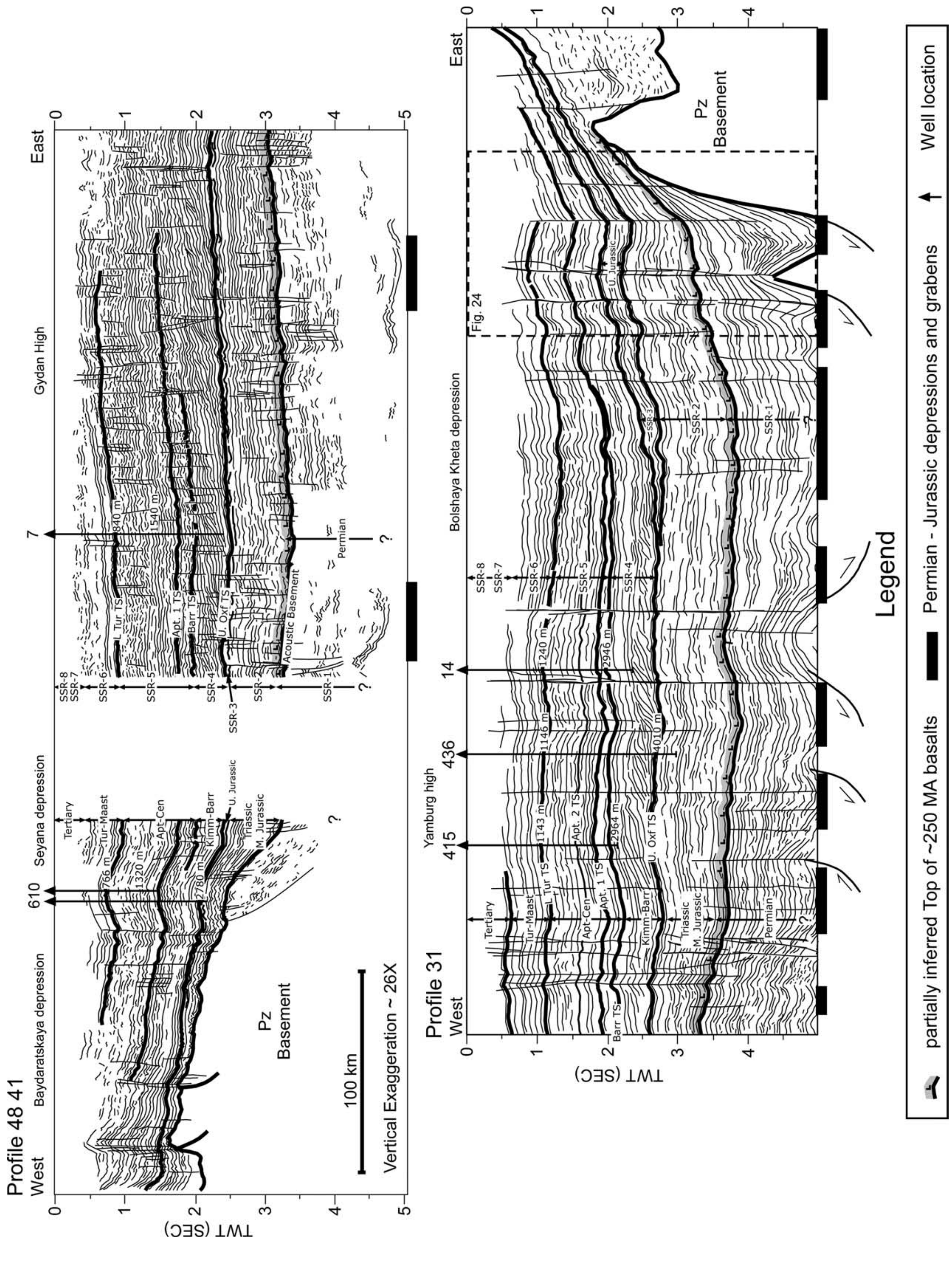

Fig. 9. Line drawing of the regional seismic profiles 31 and 4841.

Yenisey–Khatange depression, and, based on the work of Shipilov and Tarasov (1998) could extend into the Kara Sea and Barents Sea (Fig. 1). Nikishin et al. (2002) point out other localities in Eurasia, that fall outside of the area of interest selected for this paper, where Permo-Triassic flood basalts were recognized. The largest of these areas is the Emeishan flood-basalts of Southern China (Nikishin et al., 2002).

Flood-basalts are believed to be a product of major short lived mantle plumes developed under Eurasia around ~250 Ma as a result of ‘Paleozoic–Early Mesozoic global plate boundary reorganization’, which in Eurasia was associated with ‘detachment of deep-reaching inactive subduction slabs and development of new subduction zones’ (Nikishin et al., 2002). Many authors have suggested that this volcanism may be responsible for a spectacular mass extinction that occurred around Permian-Triassic time (e.g. Reichow et al., 2002; Nikishin et al., 2002; Sharma, 1997).

A one million square kilometer surface expression of Siberian flood basalts occurs in the East Siberian Platform. In the literature, it is referred to as the East Siberian Traps and/or Tunguska plateau basalts (Fig. 1). The voluminous literature on these volcanics has been summarized by Sharma (1997). The average thickness of volcanics in East Siberia is about 1 km with a maximum of about 3 km in the northwest (i.e. towards Noril’sk), thinning to a few tens of meters towards the southeast (i.e. in the direction of Yakutsk). The estimated bulk volume of the East Siberian Traps is approximately 1.752×10^6 km^3 (Vasil’ev, 1999). Sharma (1997) suggests that the eruption of these volcanics was not preceded by uplift. Instead the initial lavas were derived from a relatively deep lava source, whereas the late stage lavas were derived from a shallower mantle source.

Presence of volcanics in the West Siberian Basin is supported by a number of borehole penetrations. Locations of 20 wells penetrating basalts are shown in Fig. 1 (locations were adapted from Al’mukhamedov et al., 1998, and Reichow et al., 2002). West Siberian volcanics consist of continental flood basalts (primarily subalkaline, but also alkaline and tholeiitic) and rhyolites intercalated with shale, siltstone, and sandstone. Basaltic flows vary in thickness from tens of centimeters to 250 m (Al’mukhamedov et al., 1998; Al’mukhamedov et al., 2000a,b; Nesterov et al., 1995). A regional cross-section of five wells penetrating the Siberian basalts illustrates their composition and lateral thickness variations throughout the Basin (Fig. 10). Geochemical signatures and ages of the subalkalic basalts from the West Siberian Basin correlate with those of volcanic rocks formed during the initial stage of magmatic activities on the East Siberian Platform (Fig. 11; Reichow et al., 2002; Al’mukhamedov et al., 1998; Al’mukhamedov et al., 2000a,b). Such correlation supports an analogous formation history. The maximum penetrated thickness of volcanics in the West Siberian Basin is observed in well SG6, which encountered 1.1 km of basalts (Nesterov et al., 1995; Westphal et al., 1998; Al’mukhamedov et al., 1998; see Fig. 10). The projection of well SG-6 on a segment of regional seismic profile 25 is shown in Fig. 12. Based on the tie of SG-6 with seismic, it is apparent that the top of ~250 MA basalts correlates to the deepest strong reflector(s), marking the top of the ‘acoustic basement’. The same is believed to hold true for seismic profiles 6, 9, R1, 13, 19, 27 and 4841, as well as other regional profiles not presented in this work. Interpretation of seismic reflector(s) that correspond to Siberian basalts on regional profiles gives a good feel for their basin-wide distribution (Figs. 7–9). Examination of the slightly undulating character of the ‘acoustic basement’ may suggest that the top of the underlying, presumably Paleozoic, basement may have had a rugged paleomorphology and may not be close to an ideal peneplain (Figs. 7–9).

The presence of basalts in the Yenisey–Khatanga trough is confirmed by four well penetrations, as shown in Fig. 1. The spatial distribution of penetrations in the region (i.e. basalts were encountered in four corners of the depression) suggests the existence of basalts throughout the entire trough (Fig. 1). No information was made available on the geochemistry of these basalts; however, the authors of this paper are convinced that the Yenisey–Khatanga basalts are equivalent to basalts of the East Siberian Platform and West Siberian Basin. Outcrops of basalts in the southern Taymir Peninsula are shown on a geologic map (Fig. 1). These outcrops were determined to be composed of subaerial basaltic lavas and pyroclastics deposited, according to paleontological data, around 250 Ma (Nikishin et al., 2002; Zonenshain et al., 1993; Vernikovsky, 1996; Drachev, 1999; Inger et al., 1999; Egorov and Vavilov, 1992).

The distribution of basalts in the Kara Sea and Barents Sea is based on the interpretation of regional 2-D reflection seismic profiles and largely was not-confirmed by drilling (Shipilov and Tarasov, 1998). These authors proposed the existence of basalts in the Barents Sea, directly west of Novaya Zemlya. The existence of basalts is based on the character of the seismic data that is believed to be representative of basalts (Fig. 1). An equivalent effort was made by the same authors in the Kara Sea and is summarized in Fig. 13. Note that authors of this paper took the liberty of reinterpreting the top of the inferred basalts on Fig. 13 using data from the West Siberian Basin described earlier in this chapter. Both the original and modified interpretations are possible and both suggest the presence of basalts in the Kara Sea (interpretations are shown on Fig. 13). Neither interpretation rejects the possibility that basalts believed to be present in the Kara Sea are in fact ~250 Siberian flood basalts. However, shallower basalts (as interpreted by the authors of this paper) would suggest that the rifting observed in the Kara Sea is related to the Permian rifting event in the West Siberian Basin, whereas deeper basalts (interpreted by Shipilov and Tarasov, 1998) would suggest post basalt (younger) rifting in the Kara Sea. The authors of this paper believe that continuation of Siberian traps and a Permian rifting event in the Kara Sea is very plausible.

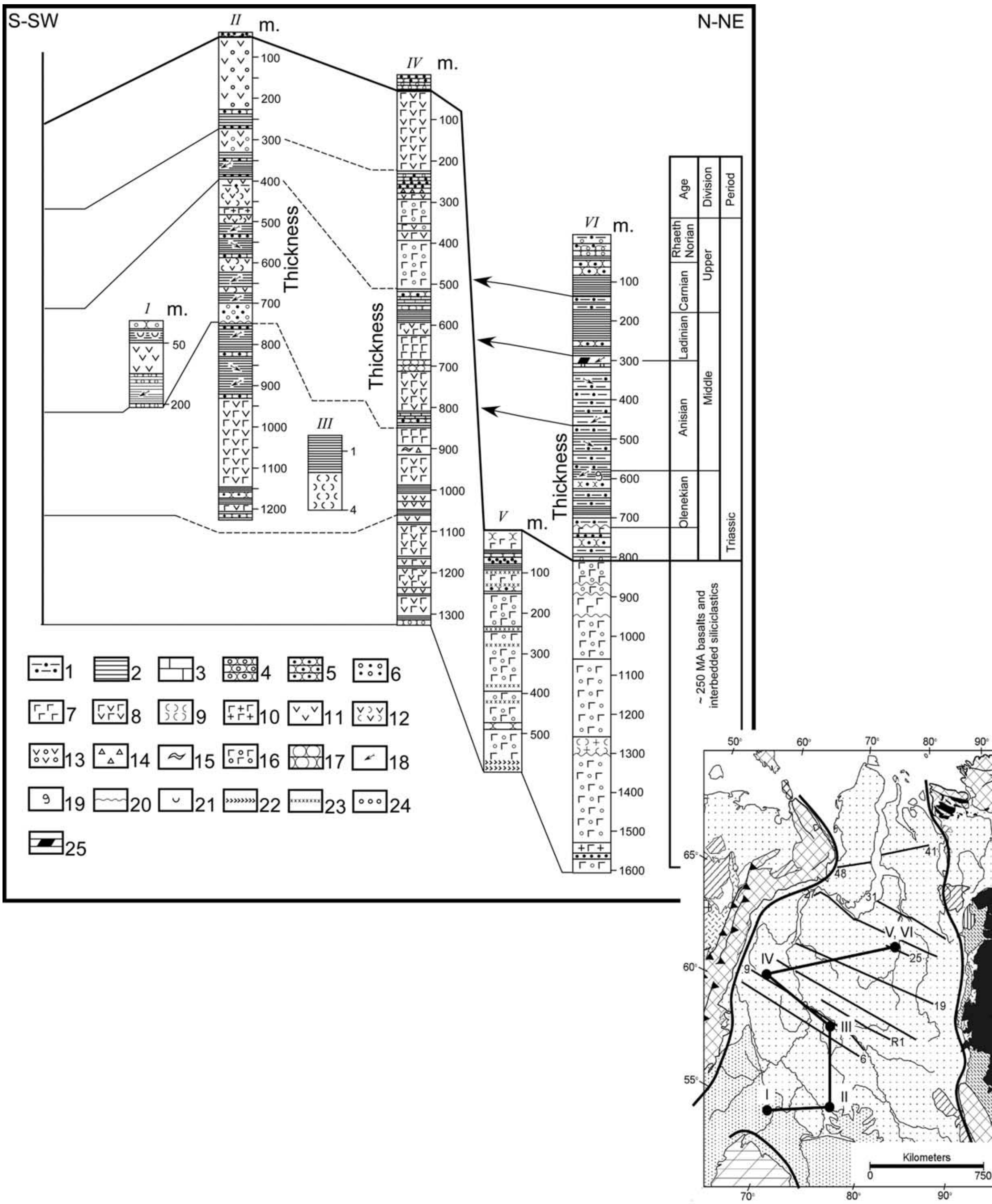

Fig. 10. Schematic cross-section of volcano–sedimentary complex modified from Al'mukhamedov et al. (1998). Note that ages and correlations between wells were modified by authors of this paper based on age determination of Reichow et al. (2002). Lithologic columns were unchanged. (I) Lebyazh'ev 1; (II) Nikol'sk 1/P; (III) Asomkinsk 2/P; (IV) Krasnoleninsk 851; (V, VI) a fragments of the SG-6. (1) Siltstone; (2) shale; (3) limestone; (4) gritstone; (5) sandstone; (6) conglomerate; (7) aphyric basalt; (8) porphyritic basalt; (9) tuff; (10) diabase and porphyritic diabase; (11) porphyritic rock; (12) tuffaceous porphyritic rock; (13) amygdaloid porphyritic rock; (14) breccia; (15) tuff-like lava; (16) amygdaloid basalt; (17) basaltic tuff; (18) plant remnants; (19) fossils; (20) stratigraphic unconformity; (21) red color alteration; (22) quartz-epidote; (23) lateritic crust; (24) laterite; (25) carbonaceous shale.

The Siberian volcanism documented in the literature varies from 1 Ma (Reichow et al., 2002) to 50 Ma (Al'mukhamedov et al., 1998). For the most part, short duration volcanic events were determined based on $^{40}Ar/^{39}Ar$ age dating and paleomagnetic data, whereas the long duration events were based on palynology (a detailed literature review on that subject can be found in Sharma, 1997). Because the short duration plateau basalt extrusion

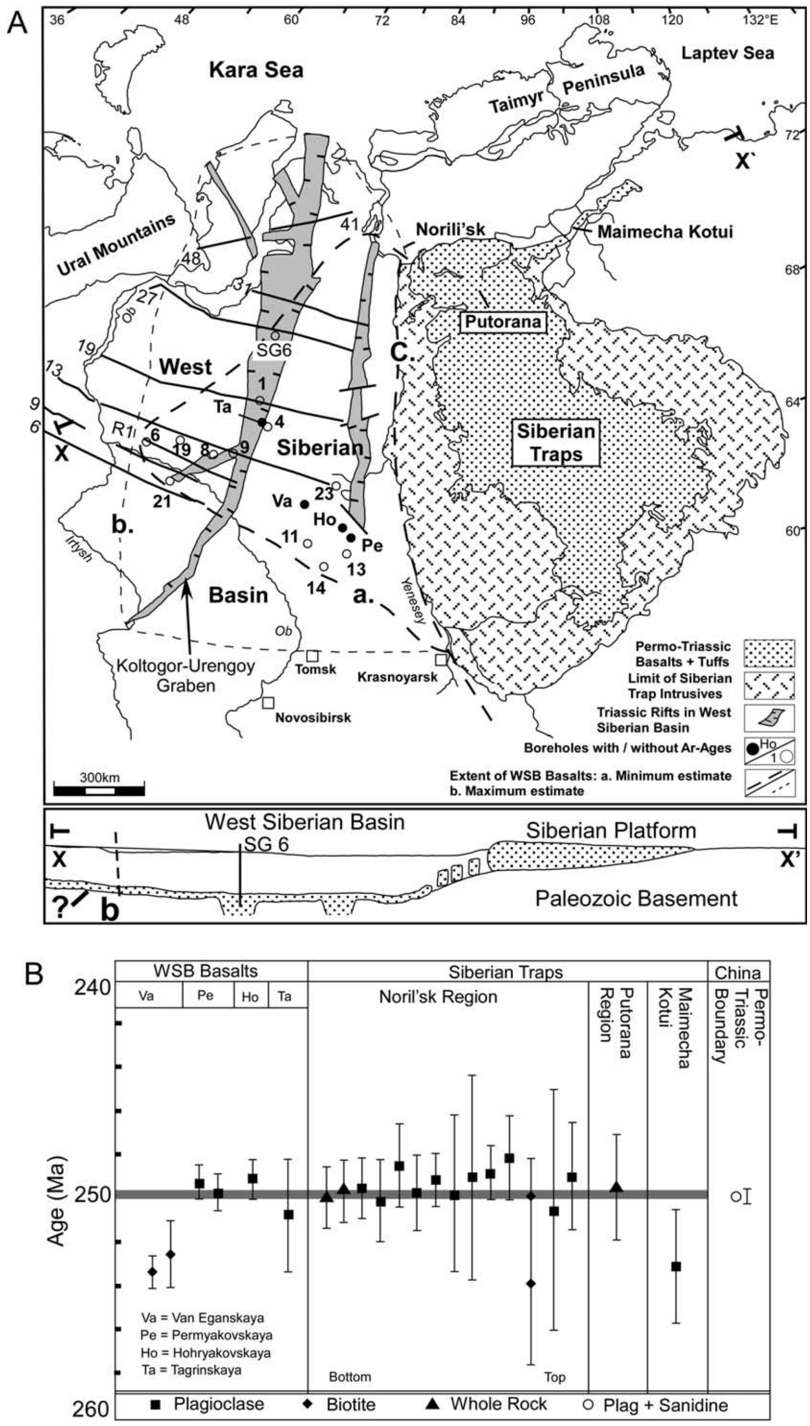

Fig. 11. (A) Simplified map and schematic cross section shown West Siberian Basin and East Siberian Platform. All boreholes shown on the map sampled basalts that were used in geochemical analysis. Wells on which 40AR/39AR analysis was performed are labeled with letters on the map (i.e. Ta = Tagrinskaya; Va = Van Eganskaya; Ho = Hohryakovskaya; Pe = Permyakovskaya). Minimum estimated area of the West Siberian Basin covered with basalts is labeled as area "a"; maximum-"b"; western limit of Siberian Platform - "c". (B) Compilation of 40AR/39AR ages of basalts (figures A and B were excerpted and modified with permission from Reichow et al., (2002) Copyright 2002 AAAS)

appears now to be commonly accepted (i.e. Nikishin et al., 2002), the authors endorse the concept that all Siberian basalts are of ~250 MA and were formed during one million years as shown in Fig. 11. Consequently, the biostratigraphic age assignment based on palynology is in doubt.

4.1.2. Remarks regarding the scale of rifting underlying the West Siberia Basins (pre SSR 1 rifting)

The scale of the West Siberian Basin graben system remains a topic of controversy. Surkov and Zhero (in Kontorovich et al., 1975) recognized a number of linear

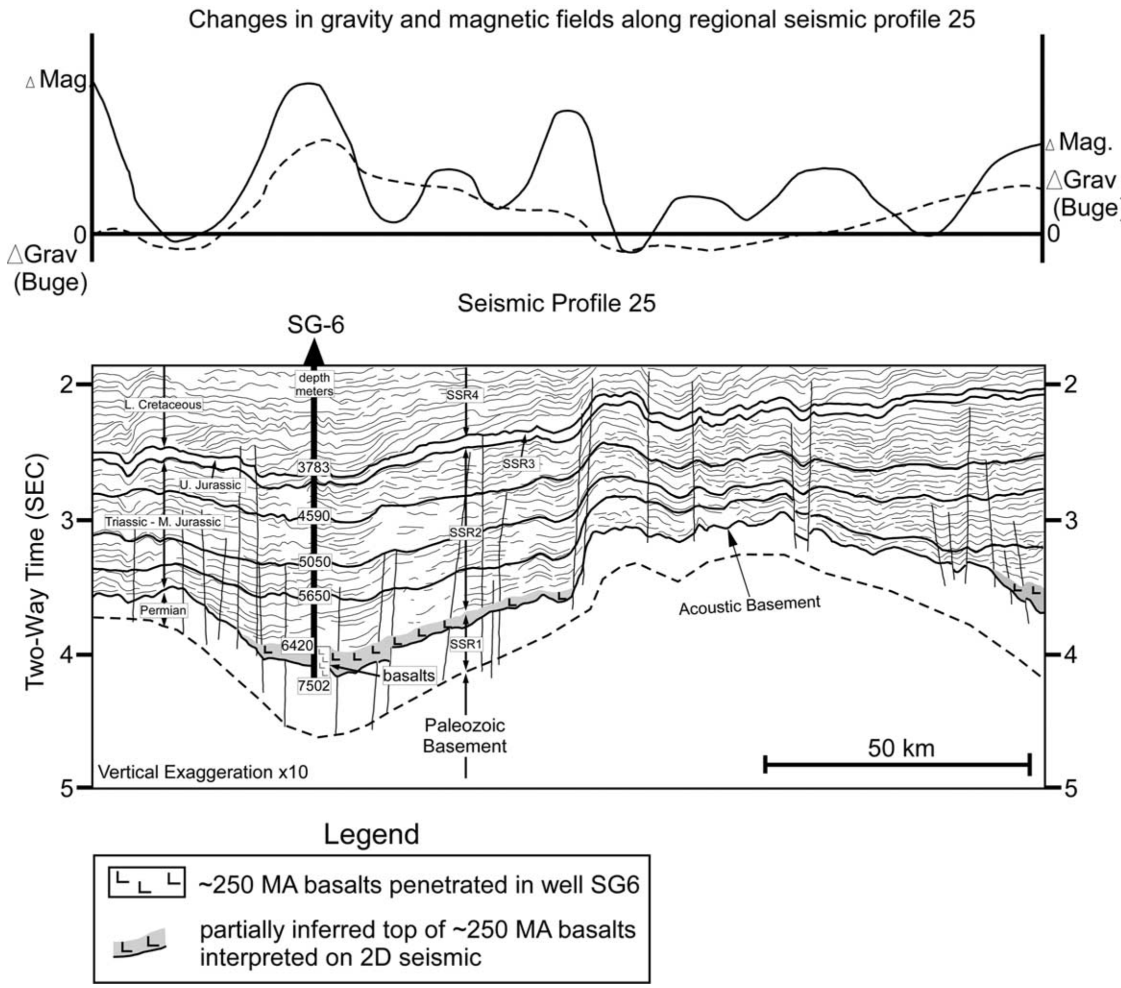

Fig. 12. Line drawing showing a segment of a regional seismic profile 25 with a superimposed well SG-6. Changes in gravity and magnetic field along the seismic profile are shown (for location see Fig. 1). Basalts were penetrated at the depth of 6420 m. Quality of the seismic data does not allow confident interpretation of basement top.

depressions on gravity and magnetic data, which they interpreted to be grabens, with the Koltogor–Urengoy being the largest (Fig. 14). In subsequent publications various authors modified hereinabove mentioned maps of graben distribution. As a result, the graben system in the West Siberian Basin varies from author to author (compare Figs. 11(A) and 14).

Little evidence for a substantial rift system is seen on regional seismic profiles (see profiles 6, 9, R1, 13, 19, and 4841 on Figs. 7–9). The two prominent exceptions to that are the Pur-Taz area and the Kara Sea (Fig. 1). The Pur-Taz area is illustrated by large grabens observed on seismic profiles 27 and 31, that show substantial infra-basalt (presumably Permian) sediments collected in fault bounded basins (Figs. 8 and 9). A significant graben fill in the Pur-Taz area was also documented by Peterson and Clarke, 1991 (Figs. 15 and 16). The Kara Sea graben system is well shown on Fig. 13 (Shipilov and Tarasov, 1998).

In an attempt to resolve an apparent inconsistency between interpretation of gravity/magnetic data and regional seismic, the interpretations of datasets were superimposed. Figs. 17 and 18 compare locations of reported linear gravity and magnetic anomalies with depressions that were observed on regional seismic profiles at 'acoustic basement' level. Locations of depressions are shown as black bars on all line drawings (Figs. 7–9) and map views (Figs. 17 and 18). Cursory inspection of Figs. 17 and 18 reveals that in Pur-Taz region locations of gravity/magnetic anomalies and depressions observed on seismic data overlap; whereas south of latitude 64° N such correlation is absent. Therefore, it is very plausible to subdivide the West Siberian Basin into two tectonic zones:

- Zone 1 —encompasses Pur-Taz region and Kara Sea, and is characterized by well defined north-south oriented Permian rift system.

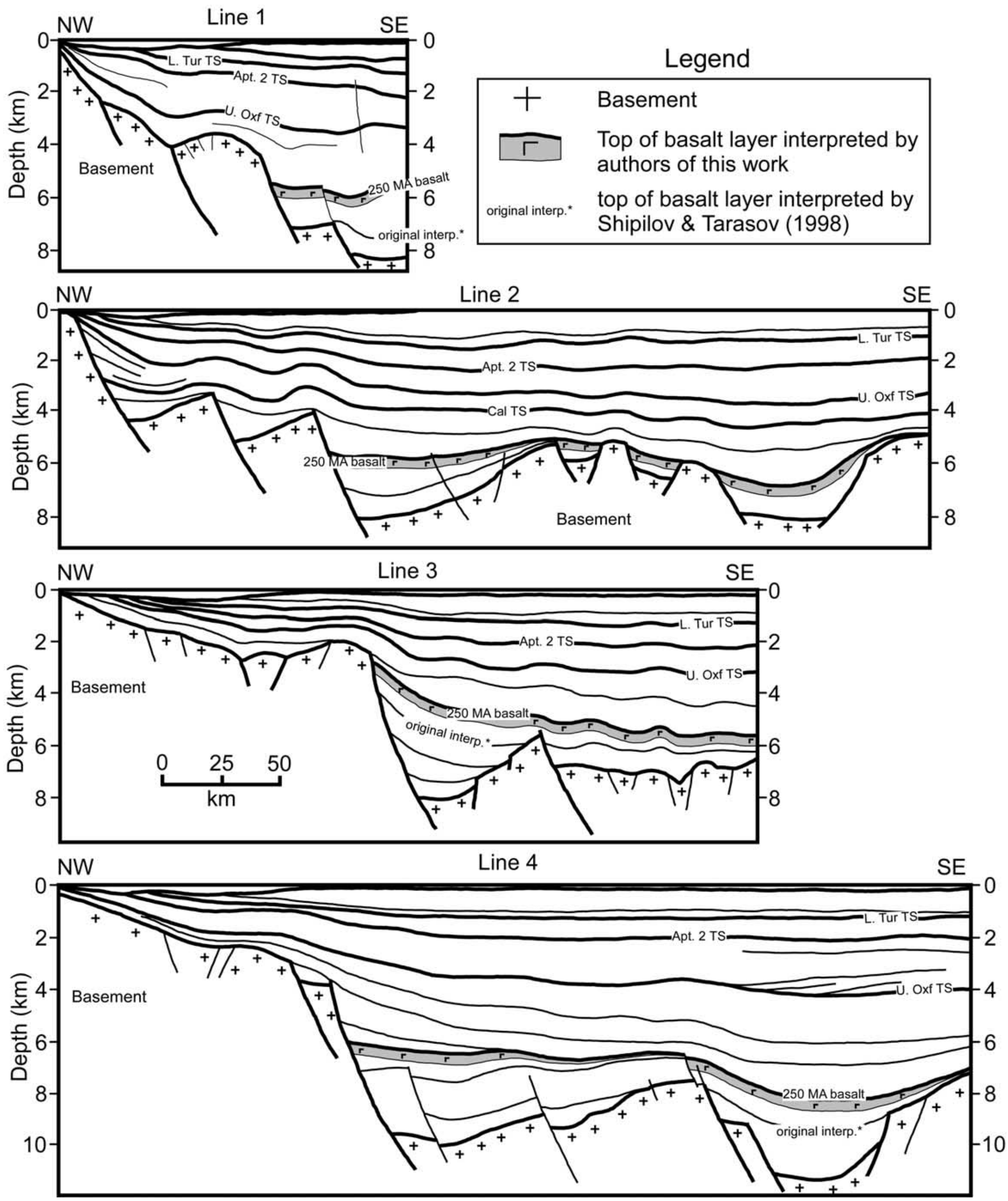

Fig. 13. Line drawings of selected seismic profiles from Kara Sea (re-drawn and modified after Shipilov and Tarasov, 1998). Location of profiles is shown on Fig. 1. Note that position of basalt reflector shown on figures above was re-interpreted by authors of this paper to be shallower then that proposed by Shipilov and Tarasov (1998). Such adjustment was made based on depth to basalts observed in the West Siberian Basin. The original interpretation made by Shipilov and Tarasov (1998) is also shown above.

- Zone 2—includes everything south of latitude 64°N, and is distinguished by broad depressions with no evidence of major graben or rift formation.

At this point it is critical to re-emphasize that distribution of ~250 MA basalts of the West Siberian Basin described in the previous section is not limited to grabens observed in Zone 1. Therefore, emplacement of basalts is not a consequence of graben formation.

4.1.3. Remarks regarding initial stages of the West Siberian Basin development

The Permian–Middle Jurassic (SSR1 and SSR2) history of the West Siberian Basin development can be considered to be a stage of pre-basin evolution. During this time the Siberian lowland (currently the West Siberian Basin and East Siberian Platform) was situated above sea-level and filled with volcanic rocks and

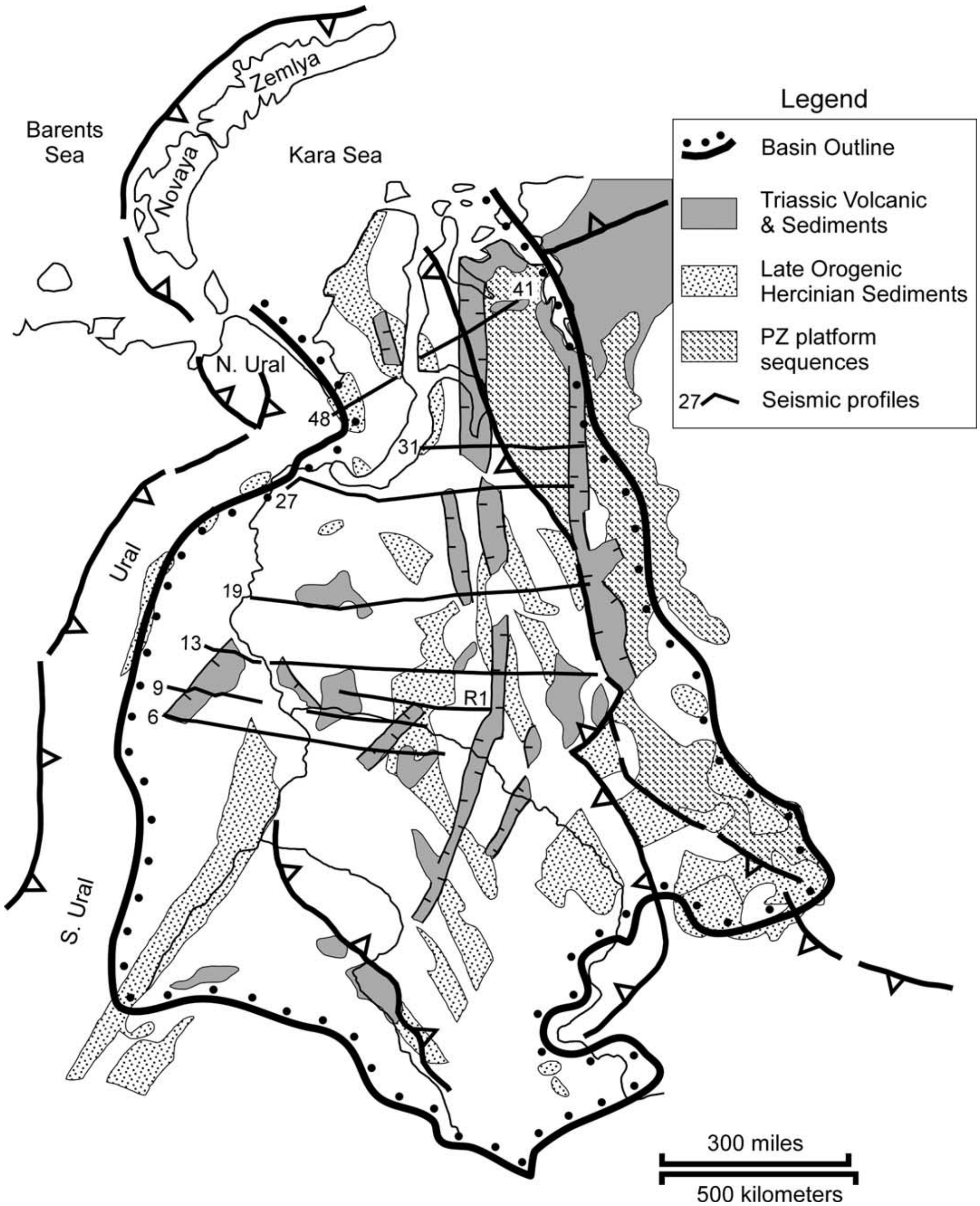

Fig. 14. Pre-Jurassic basins of the West Siberian Basin (re-drawn and modified after Kontorovich et al., 1975).

continental siliciclastic sediments deposited in low-relief sag basins. Grabens were formed only in the north-northeastern part of the West Siberian Basin (i.e. the Pur-Taz area) and the Kara Sea. Permian extrusion of Siberian flood basalts and graben formation was related to mantle plumes beneath Siberian lithosphere (e.g. Nikishin et al., 2002). Analogous to Central Europe (i.e. the Southern Permian Basin and the Variscan crust), mantle plumes may have caused 'thermal thinning' of lithosphere and 'magmatic thinning' of the crust (e.g. Ziegler, 2004; Ziegler et al., 2004). Therefore, basin-wide subsidence of the West Siberian Basin that started in the Jurassic and continued until the Tertiary, is a product of 'thermal re-equilibration of the lithosphere–asthenosphere system' following Permian plume activities (Ziegler, 2004). It should be noted that the basalts which filled the shallow basin in the Permian (and potentially lower Triassic) today occur as deep as 6400 m in the West Siberian Basin as well as on the surface at Tunguska plateau (East Siberian Platform). Lack of subsidence at Tunguska plateau may be explained by its lower density. According to Artemieva and Mooney (2001), Archean and early Proterozoic mantle lithosphere is found to be 1.5% less dense than the underlying asthenosphere. This buoyancy may have prevented the East Siberian Platform from subsiding.

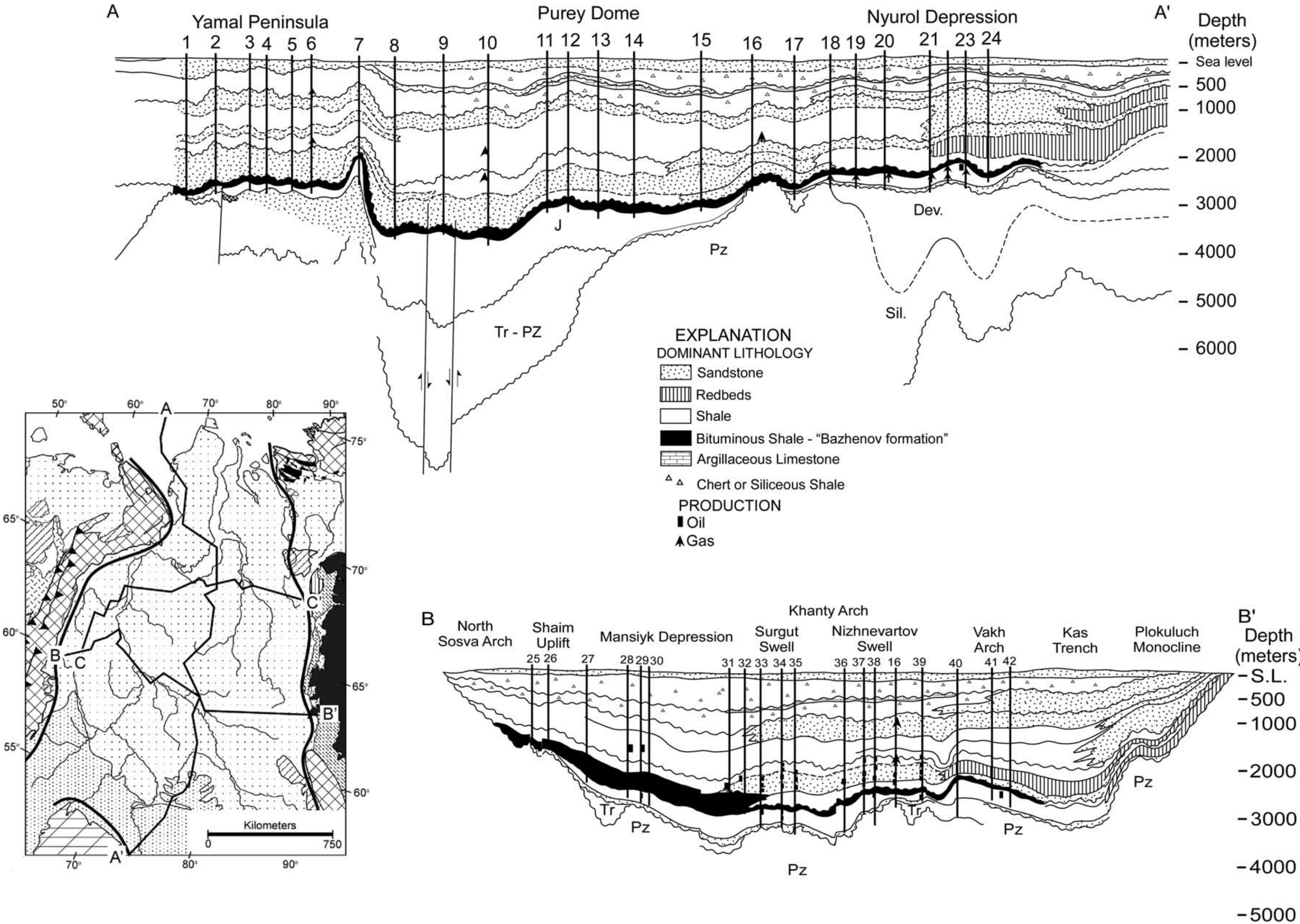

Fig. 15. Structural-stratigraphic facies cross sections (re-drawn and modified after Peterson and Clark, 1991).

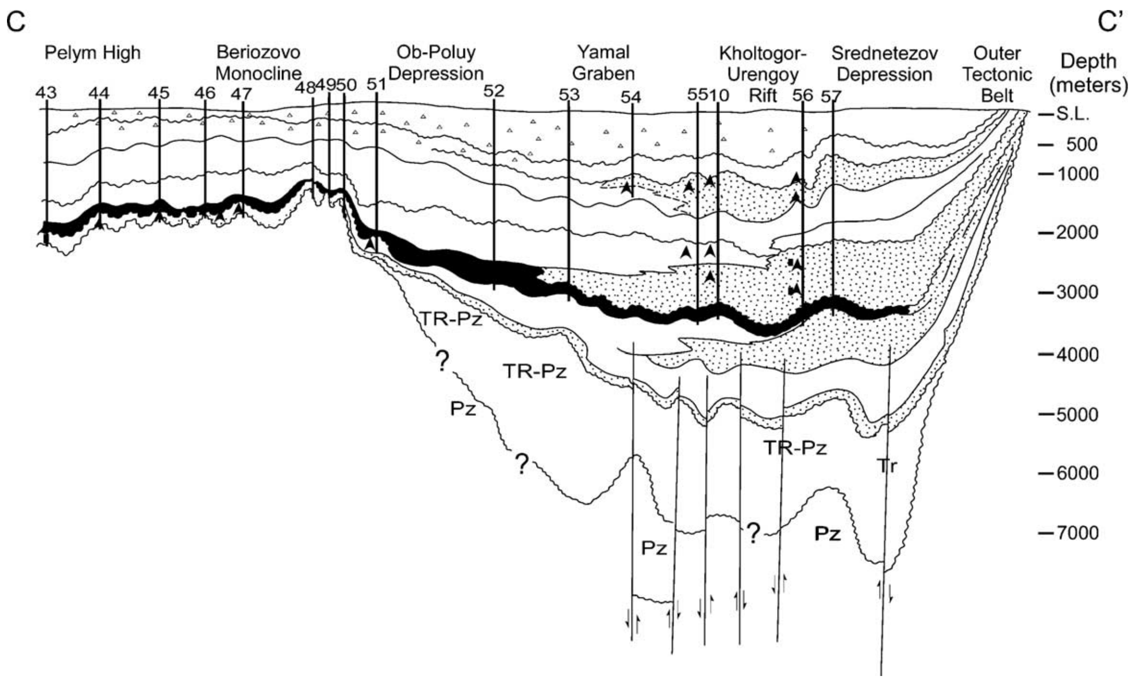

Fig. 16. Structural-stratigraphic facies cross section (re-drawn and modified after Peterson and Clark, 1991). For location map see Fig. 15.

4.2. History of stratigraphic studies in the West Siberian Basin

Regional stratigraphic studies of the West Siberian Basin began in the 1960s, and were primarily based on well-log data, core samples, and outcrops. Due to the lack of seismic data, a 'layered cake' framework for deposits of the Triassic–Quaternary interval was initially developed in publications of Rostovtsev (1961, 1970); Nesterov and Prozorovich (1968); Nesterov et al. (1968); Nesterov (1969); Nesterov and Poteriaeva (1971); Nesterov and Ushatinskii (1971); Kontorovich et al. (1975); Rudkevich (1971); Braduchan et al. (1968), and many others. According to these publications, the West Siberian Basin was characterized by sub-parallel layers of siliciclastic sediments that were traced from the basin's margins to its center.

Naumov first recognized the clinoform geometries of the Neocomian sediments in the 1970s (Vyssotski, 1993). Researchers from the West Siberian Geological Institute and West Siberian Geophysical Institute, upon the completion of regional seismic surveys, were able to demonstrate and refine Naumov's observations on seismic profiles. A seismic/sequence stratigraphic approach to the interpretation of seismic profiles from the West Siberian Basin was pioneered by Kornev and Karogodin and currently is widely accepted and used by industry and academia (see Kornev et al., 1982; Karogodin, 1974; Karogodin and Nezhdanov, 1988; Nezhdanov and Kornev, 1984; Nezhdanov, 1993; Vyssotski, 1987; Vyssotski, 1993; Kunin, 1993; and other scientists). Nevertheless, the 'layer cake' model left a significant imprint on the stratigraphy of the West Siberian Basin. The stratigraphic nomenclature in the West Siberian Basin was primarily developed according to 'layer cake' model and later modified and partially adopted by sequence stratigraphers.

4.3. Triassic–Eocene sequence stratigraphy

From the Callovian basin-wide transgression until Tertiary uplift, the stratigraphy of the basin was strongly influenced by eustasy. The differentiation between the effects of tectonics and eustasy in cratonic basins is simple—the global eustatic signal is basin-wide and is enhanced by regional and local tectonics. The most spectacular element of the West Siberian Basin stratigraphy is a series of westward prograding clinoforms of Kimmeridgian–Barremian age.

4.3.1. Sequence stratigraphic methodology

Sequence stratigraphic analysis was applied to create a depositional model for the West Siberian Basin. Preference was given to the methodology and basic terminology proposed by Vail, et al. (1977a,b, 1991); Mitchum (1977); Posamentier et al. (1988); Van Wagoner et al. (1990); Mitchum and Van Wagoner (1991); Embry (1995, 1997). However, deviations from the standard approaches were made to accommodate the unique depositional history of the West Siberian intracratonic basin. The methodology used in this work is a tailoring of concepts developed by the above listed authors.

The key sequence stratigraphic unit described in this work is the 3rd order transgressive–regressive (T–R) composite sequence (Fig. 19). In the basin, slope, and shallow-shelf depositional environments, the 3rd order T–R composite sequence is bounded by conformable

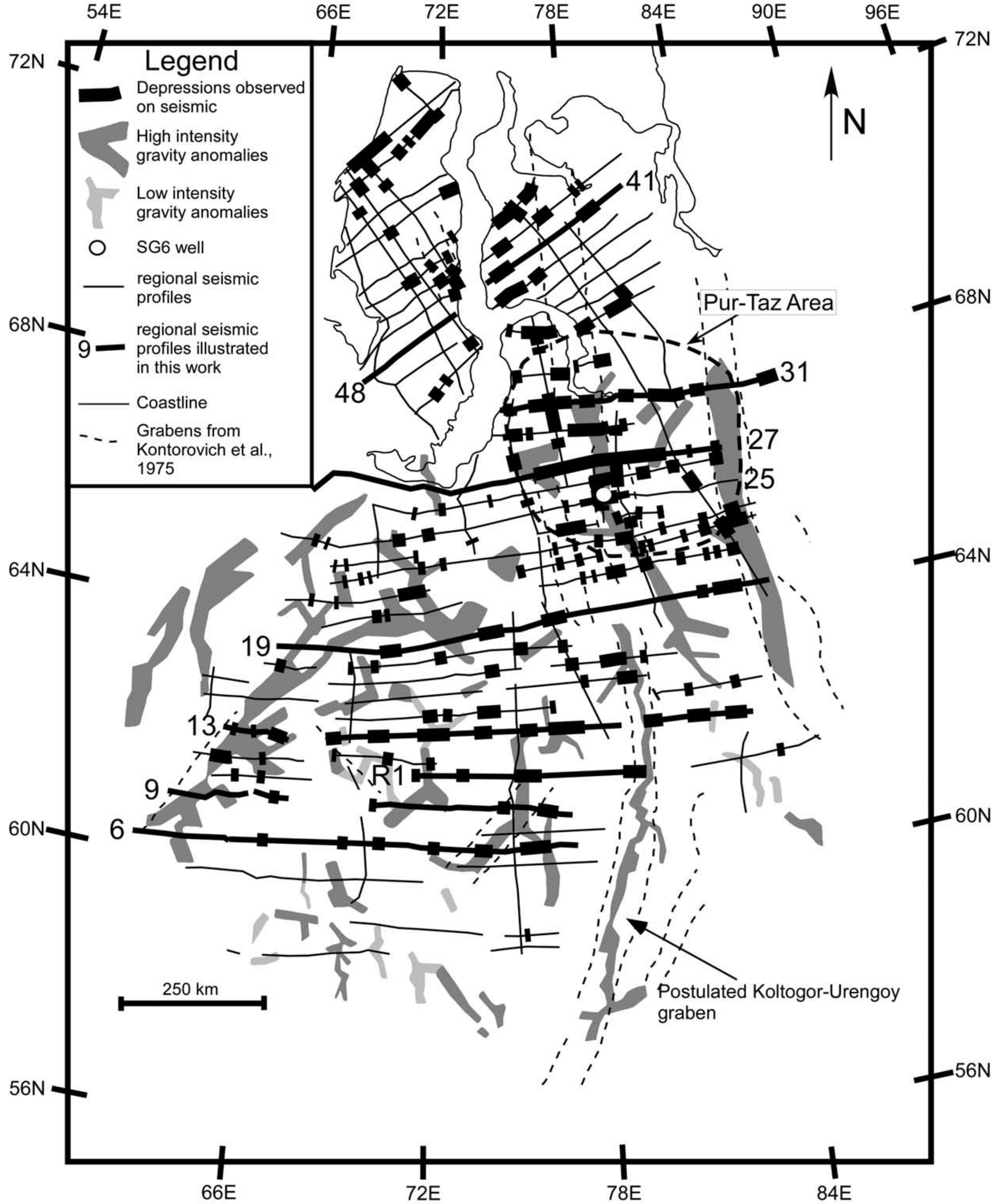

Fig. 17. Map of the West Siberian Basin showing relationship between locations of gravity anomalies and depressions observed on the regional seismic profiles (courtesy of Kosarev, I., chief research geoscientist at TyumenNIIgiprogas, Tyumen, Russia). Grabens interpreted by Surkov and Zhero in Kontorovich et al., 1975 are shown in dash line (same grabens are shown in Fig. 14).

transgressive surfaces. On the shallow shelf, the transgressive ravinement surfaces often merge with an unconformity produced by sea-level fall (available seismic data do not allow differentiation of subaerial unconformities and ravinement surfaces). Analogous to the composite sequence of Mitchum and Van Wagoner (1991), the T–R composite sequence is divided into lowstand, transgressive and highstand sequence sets that consist of 4th order sequences, which in turn can be divided into parasequences (Fig. 19). This subdivision

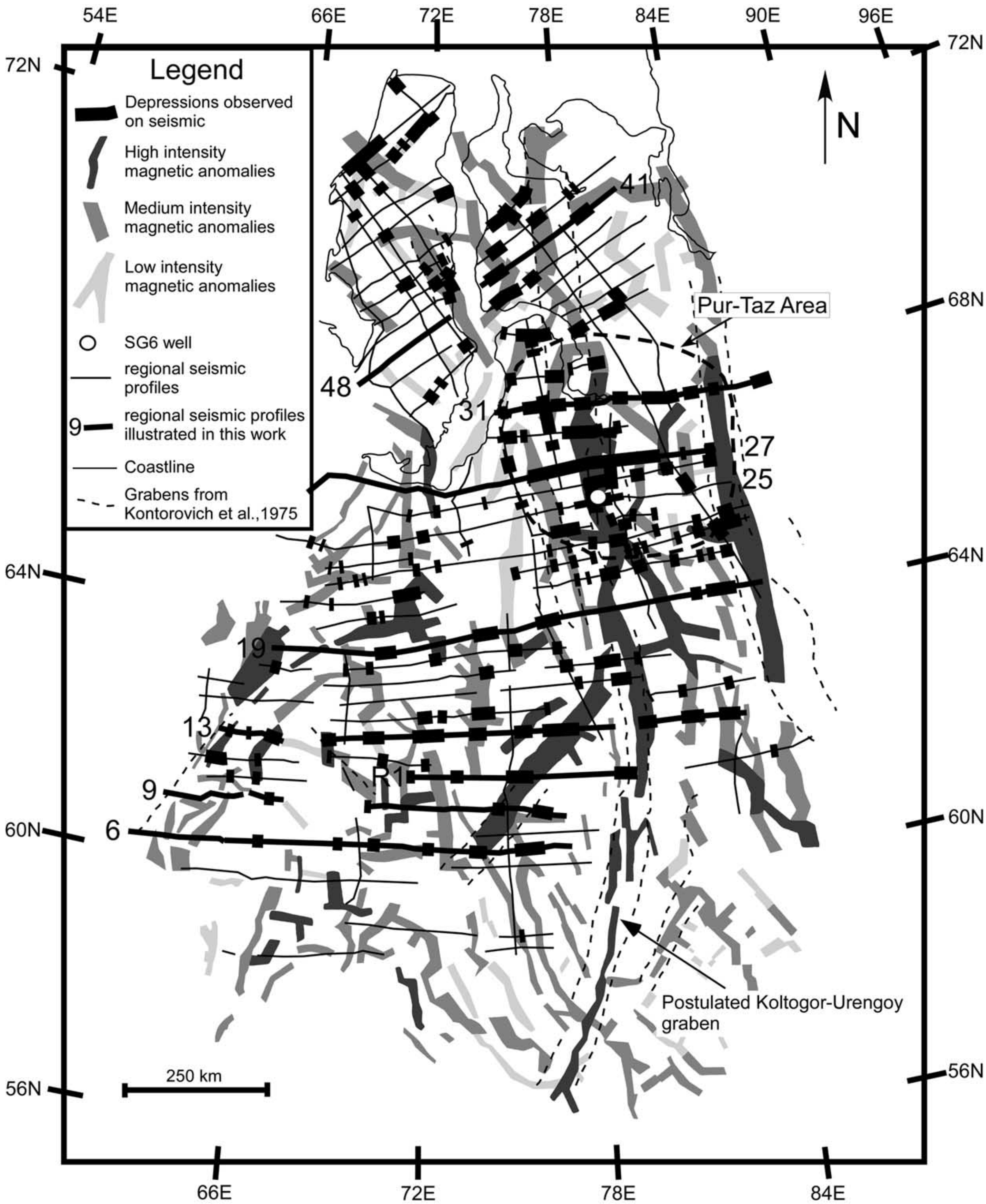

Fig. 18. Map of the West Siberian Basin showing relationship between locations of magnetic anomalies and depressions observed on the regional seismic profiles (courtesy of Kosarev, I., chief research geoscientist at TyumenNIIgiprogas, Tyumen, Russia). Grabens interpreted by Surkov and Zhero in Kontorovich et al., 1975 are shown in dash line (same grabens are shown in Fig. 14).

emphasizes that unconformities associated with sea-level fall are considered to be as important as transgressive and flooding surfaces. The transgressive sequence sets are thin and, on conventional seismic data, have been interpreted to be single, high amplitude, regionally correlative reflectors. The following reasoning is offered to justify this approach:

- The presence of transgressive deposits underlain by a transgressive surface and overlain by a flooding surface

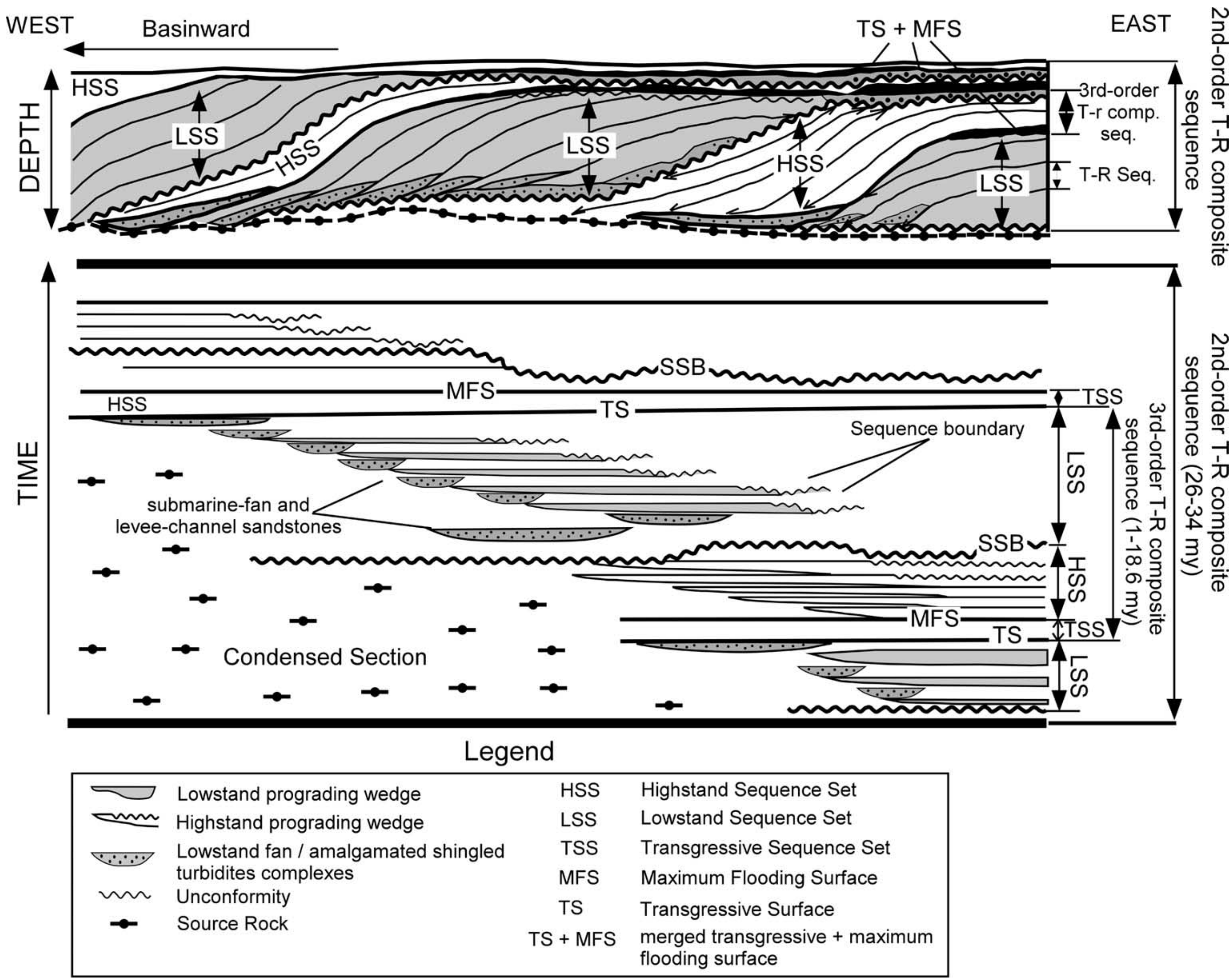

Fig. 19. Stratigraphic and chronostratigraphic diagram of the transgressive–regressive (T–R) composite sequence illustrating methodology adopted in this paper (modified after Vyssotski, 2001). All sequence sets are composed of sequences.

can be clearly documented on seismic and well-log data. Nevertheless, the positioning of the unconformities in the offshore shelf, slope, and basin is less certain in the West Siberian Basin.
- The interpreted flooding surfaces have been dated and related to ammonite zones, thus adding a degree of certainty to the correlation. The biostratigraphic work was performed by a number of organizations and summarized by the 'Fifth Tyumen Regional Stratigraphic Symposium' held on May 18, 1991 (see Belousova et al., 1991 for the original report; a copy of this report can also be found in Vyssotski, 2001).
- The documented transgressive surfaces are believed to be regional, whereas the regional extent of the unconformities has not been demonstrated with the available data.
- A transgressive surface separates all transgressive deposits from all regressive deposits.

A detailed sequence stratigraphy can only be resolved for the Kimmeridgian–Cenomanian interval. Even in this interval, the 3rd order cycles cannot be determined in the Kimmeridgian–Berriasian time due to the limited eastward extent of the regional seismic data. Seismic resolution of the Barremian–Cenomanian interval only permits the identification of large groups of cycles. The physical characteristic of any unit is interpreted from the seismic data and calibrated to the well log data (Figs. 7–9 and 20). The hierarchy of the 1st, 2nd, and 3rd order cyclicity has been assigned to the deposits of the West Siberian Basin (Fig. 2). The 1st, 2nd and 3rd order cyclicity is controlled by sea-level variations—possibly of eustatic origin, whereas 4th order events are controlled by changes in the supply of sediments.

4.3.2. Sequence stratigraphy

First, second, and third order composite sequences have been interpreted using the methodology described hereinabove. The definition of a sequence order is arbitrary and it depends on the resolution of the seismic and well log data. The west–east oriented regional well cross-section shown in Fig. 20 demonstrates major 2nd and 3rd order transgressive–regressive (T–R) sequences observed in the central part of the basin. On a basin-wide scale, one 1st order T–R cycle, that reached its peak transgression in the Lower Turonian, was identified (Fig. 2). Four 2nd order T–R composite sequences were recognized and divided into 16 3rd order T–R composite sequences observed within the limits of seismic data (Fig. 2). The presence of the 4th order events is evident on all regional seismic profiles; however, a grid of higher resolution 2-D or 3-D seismic data is required to further constrain the interpretation. The 4th order T–R sequences are recognized on a field scale 2-D seismic grid (Vyssotski, 2001). It is believed that the autocyclic events controlled by delta shifting and variations in the sedimentary supply dominate the formation of the 4th order sequences.

4.3.2.1. SSR2 Triassic–L. Jurassic. The base of this unit is the top of the volcanic sequence, and the top is the Callovian transgressive surface (Figs. 7–9 and 20). SSR2 consists of continental deposits, i.e. light gray sandstones, shale, and siltstones, with thin layers of coal and conglomerates (Kontorovich et al., 1975; Belousova et al., 1991). Coaly detritus, plant remnants, plant imprints, and paleo-soils are very common. All age dating of this unit is based on palynology. The nature of the depositional environment along with the resolution of available data does not allow detailed interpretation within this unit.

4.3.2.2. SSR3 Callovian–Oxfordian. SSR3 is a 2nd order T–R composite sequence—the base of which corresponds to the first basin-wide Callovian transgression (Figs. 7–9 and 20). This transgression is characterized by a marine invasion in the north and east. During this time interval, the depositional environment in the West Siberian Basin changed from continental (Tyumen formation) to marine (Georgiev formation, etc., Fig. 2). Hence, lithologies changed from non-marine gray shale, siltstone and sandstone (plant detritus and pyrite are common) to dark-gray or black silty shales in parts bituminized and glauconitic. In the central part of the basin, the SSR2 unit is relatively thin ($\sim$50 m). In the north-eastern portion of the basin, this unit expands into a thick ($\sim$500 m) westward prograding package as shown on the seismic profile 31 (Fig. 9). The SSR3 unit is dated by ammonites, bivalves and foraminifera as Callovian–Oxfordian in age. Pinous et al. (1999) determined that a late Bathonian transgression marks the beginning of a marine regime and have subdivided the SSR3 unit into several third-order cycles (Fig. 2). These cycles, Pinous et al. (1999) assert, can be convincingly correlated with equivalent cycles on the Russian platform to the west, thus are likely to be due to eustatic sea-level changes.

4.3.2.3. SSR4 Kimmeridgian–Barremian. SSR4 is a 2nd order T–R composite sequence underlain by a major transgressive surface (Figs. 7–9 and 20). A maximum basin wide transgression began in the uppermost Oxfordian time and was followed by a spectacular series of prograding, relatively high angle clinoforms, all merging into the basinal organic-rich brownish-black Bazhenov shales. These shales are the principal source rocks of the West Siberia Basin and can be up to 50 m thick (Fig. 21(A)). Shales are dated as Kimmeridgian–Hauterivian in age, again mainly on the base of ammonites and foraminifera (Belousova et al., 1991). The paleo-water depth established during this time reached 1200 m in the basin center (based on decompaction using porosity vs. depth curve of Bond and Kominz, 1984). Within an area coverage of the available data, prograding clinoforms were grouped into sixteen 3rd order T–R composite sequences (Fig. 2). Note that on Figs. 7–9, 21 and 22 the

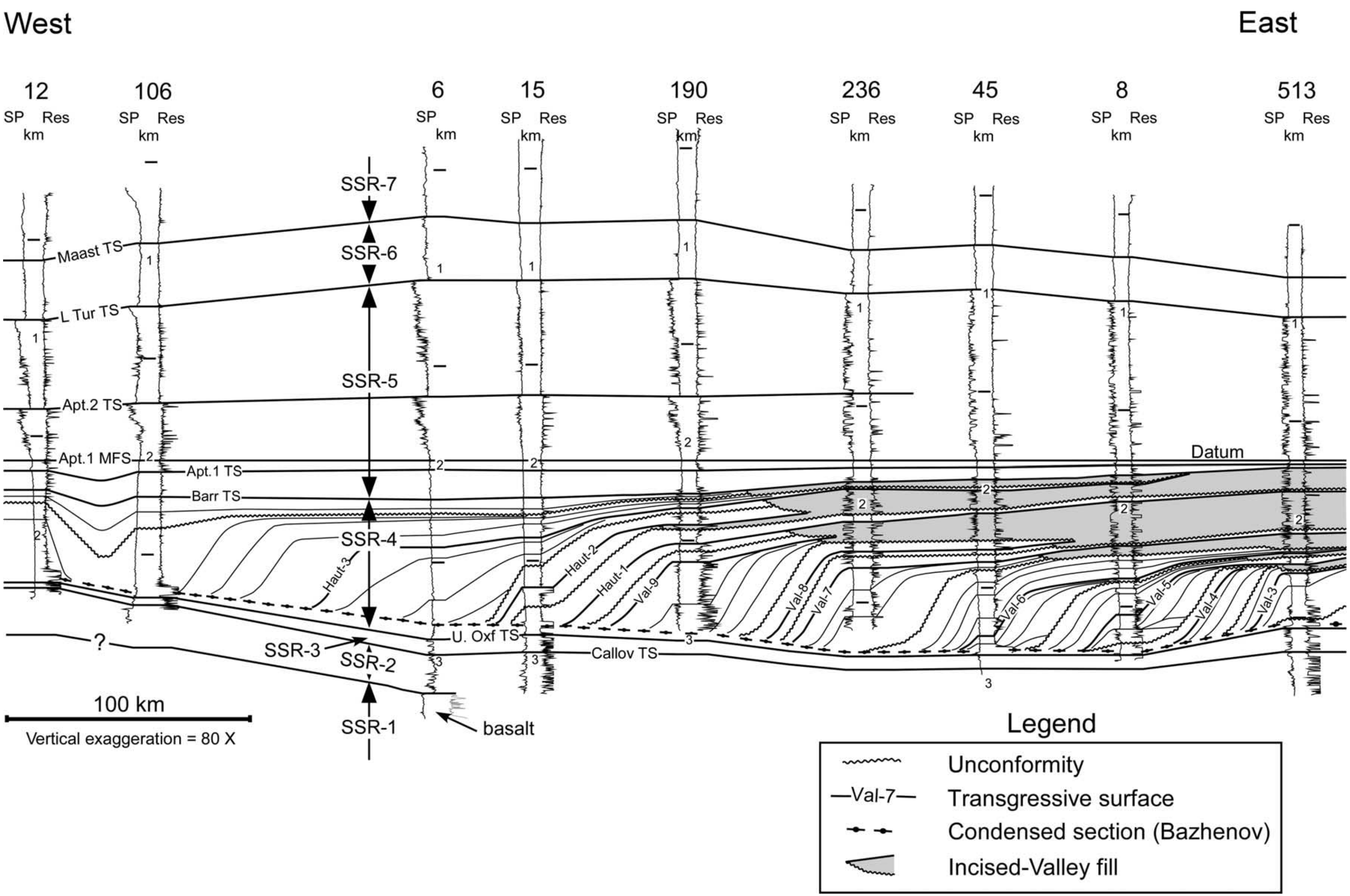

Fig. 20. Stratigraphic well log cross section along seismic profile 9. List of complete well names: Potanay 12, Pottym 106, Khanty-Mansisk 6, Khanty-Mansisk 15, Salym 190, Ust'-Balyk 236, East-Surgut 45, Pokamas 8, S-Oreh 513.

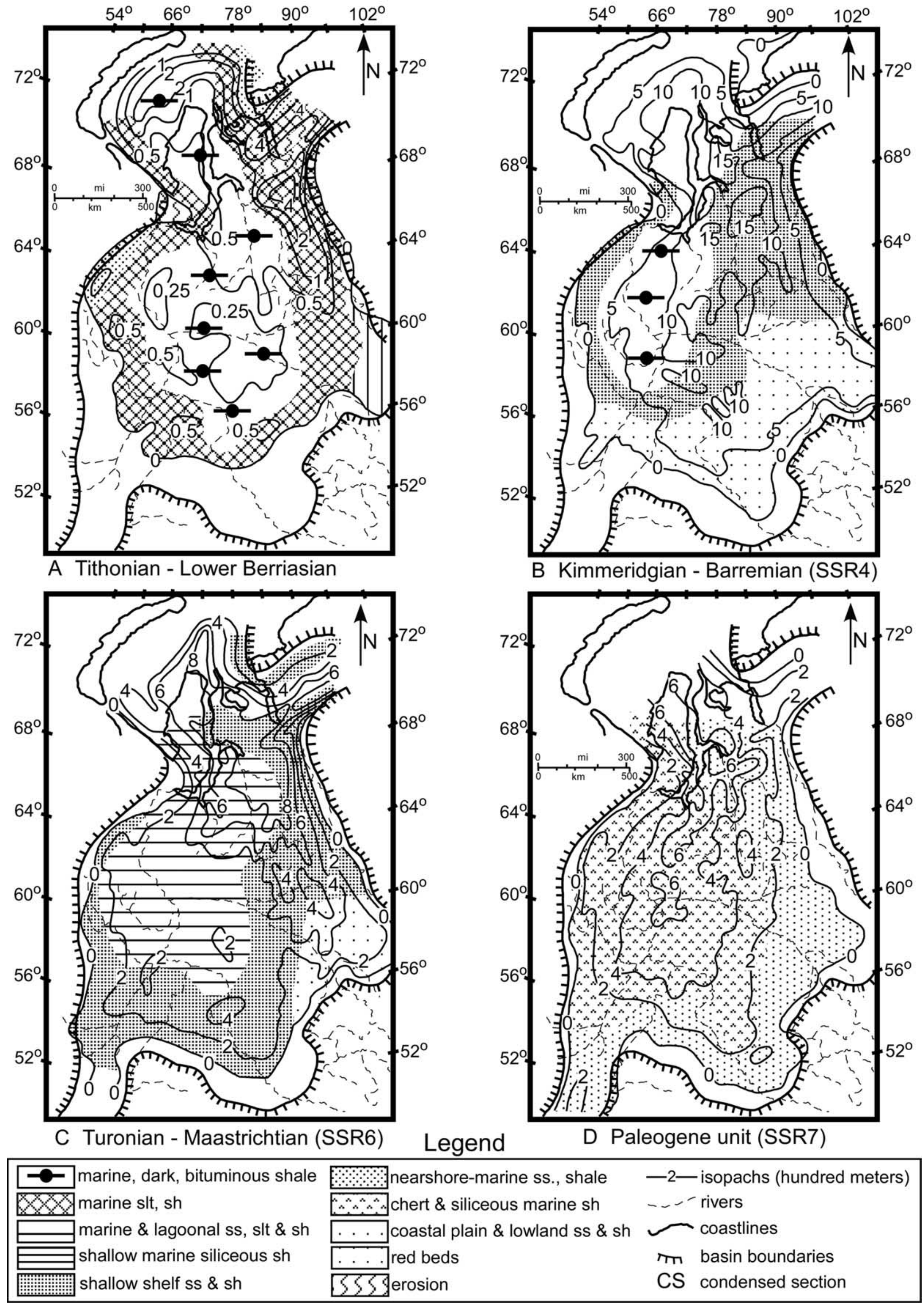

Fig. 21. Litho-facies/isopach maps of the West Siberian Basin (re-drawn and modified after Rudkevich, 1988). (A) Tithonian—Lower Berriasian. (B) Kimmeridgian—Barremian (SSR4). (C) Turonian—Maastrichtian (SSR6). (D) Paleogene unit (SSR7).

main clastic input in this composite sequence is from the Siberian platform to the east, with only a minor source from the Urals to the west as shown by Fig. 23. The sparse siliciclastic input from the Ural Mountains can be explained by their relatively low relief (Puchkov, 1997). A detailed sequence-stratigraphic well cross-section selected along seismic profile 9 demonstrates the depositional geometries of 3rd order T–R composite sequences developed within the SSR4 (Fig. 20). The wide range of SSR4 deposits are composed of siliciclastic sediments from the following environments: non-marine (alluvial, lacustrine, fluvial, incised valley fill, coastal plain); shallow marine (bars, beaches), and marine (distal condensed sections, deep water and slope turbidities, shelf margin deltas). The thickness of SSR4 ranges from 0.5 to 1.5 km (Fig. 21(B)). Significant uplifts and depressions were formed during this time and are described in Section 4.4 of this paper. The main oil reserves are found within this unit.

4.3.2.4. SSR5 Aptian–Cenomanian. SSR5 is a 2nd order T–R composite sequence underlain by a major transgressive surface (Figs. 7–9 and 20). SSR5 consists of three westward prograding transgressive–regressive composite sequences produced by 3rd order cyclicity (Fig. 2). The Aptian–Cenomanian depositional environment was continental to the east and marine to the west. Lithologies vary from non-marine sandstone and shale—in places with coal deposits and amber to the east—to marine shale with an occasional thin bed sandstone, siltstone and limestone to the west (Kontorovich et al., 1975; Belousova et al., 1991).

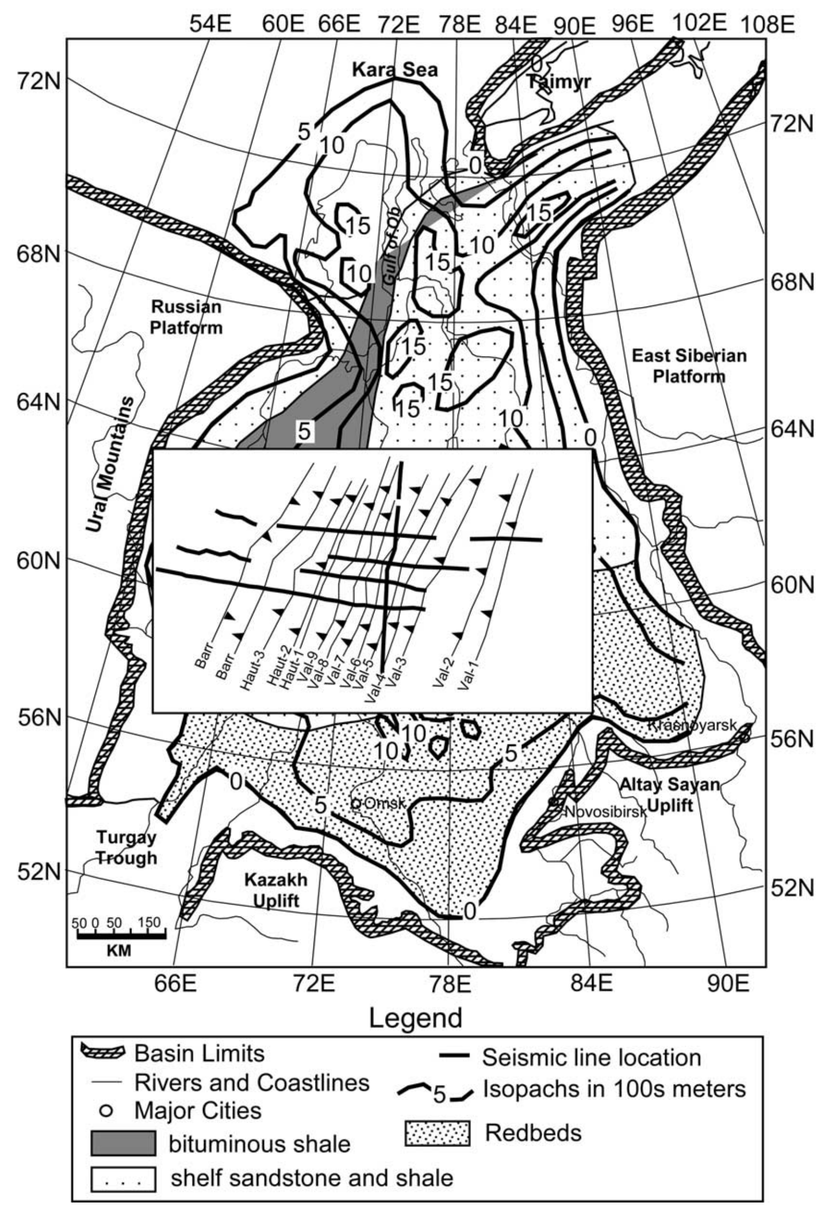

Fig. 22. Direction of progradation and shelf-break orientation of the Oxfordian–Barremian deposits of the West Siberian Basin (modified after Vyssotski, 2001). Isopachs show thickness of the Neocomian sediments in hundreds of meters (modified after Rudkevich, 1988).

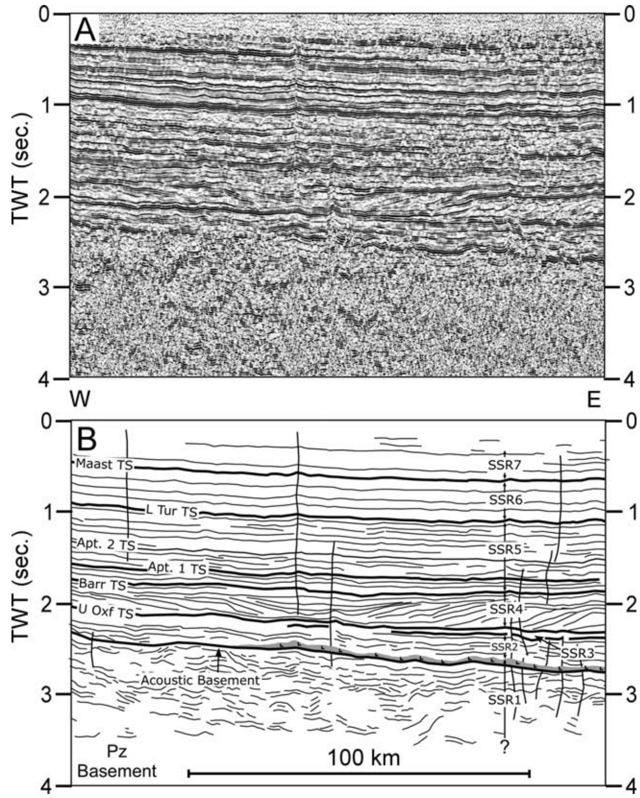

Fig. 23. Details of the regional seismic profile 19 illustrating progradation from the east and west. (A) Un-interpreted seismic section. (B) Line drawing. See Fig. 8 for location.

Paleontological control for the marine facies of these sequences is based on foraminifera and ostracods, whereas the coastal deltaic facies are defined through plants and palynological evidence (Belousova et al., 1991). The paleo water depth established during this time reached 400 m in the basin center (based on decompaction using the porosity vs. depth curve of Bond and Kominz, 1984). The prograding nature of these sediments is not readily recognizable on regional seismic profiles, but inferred from subsurface data. Seismic of higher resolution is required to better image the prograding beds. The primary gas reservoirs, particularly in the northern part of the basin, are associated with this unit.

4.3.2.5. SSR6 Turonian–Maastrichtian. SSR6 is a 2nd order T–R composite sequence, the base of which presumably corresponds to a global transgressive event (Figs. 2, 7–9 and 20). Resolution of available data prevents recognition of 3rd order cyclicity in this unit. SSR6 is composed of marine and continental deposits: shale, siltstone, fine-grained sandstone, and marls sourced from the east (Fig. 20). The thickness of this section reaches 800 m (Fig. 21C). Paleontological control for SSR6 is based on foraminifera and belemnites (Belousova et al., 1991). The paleo water depth established during this time appears to be up to 500 m in the basin center (based on decompaction using porosity vs. depth curve of Bond and Kominz, 1984). The Turonian interval is characterized by a regional transgression, followed by the re-opening of the West Siberian Basin to the Arctic ocean.

4.3.2.6. SSR7 Maastrichtian—Eocene. SSR7 is poorly imaged in the available dataset. This unit is composed of shale, siltstone, fine sandstone, and marls (Figs. 7–9 and 20). SSR7 reaches a thickness of 600 m (Fig. 21D). In the Eocene epoch, the West Siberian Basin experienced the maximum transgression of the Paleogene; moreover, at the end of the middle Eocene, 80% of the Basin was covered by the sea (Shatski et al., 1996). Glauconitic sandstones observed in the early Eocene exhibit strong support for a basin-wide transgression.

4.3.2.7. SSR8 Oligocene—recent. We are unable to subdivide the SSR8 interval based on the available data. Much higher resolution data would be required to get a better understanding of its internal architecture. According to Shatski et al. (1996), the paleogeographic environment of the West Siberian Basin changed abruptly at the Eocene–Oligocene boundary from marine to continental as a result of uplifts that started in late Eocene and culminated around the Eocene–Oligocene boundary. The late Eocene marine glauconitic shales, rich in pyrite and siderite, gave way to Oligocene continental sands and the coal rich deposits.

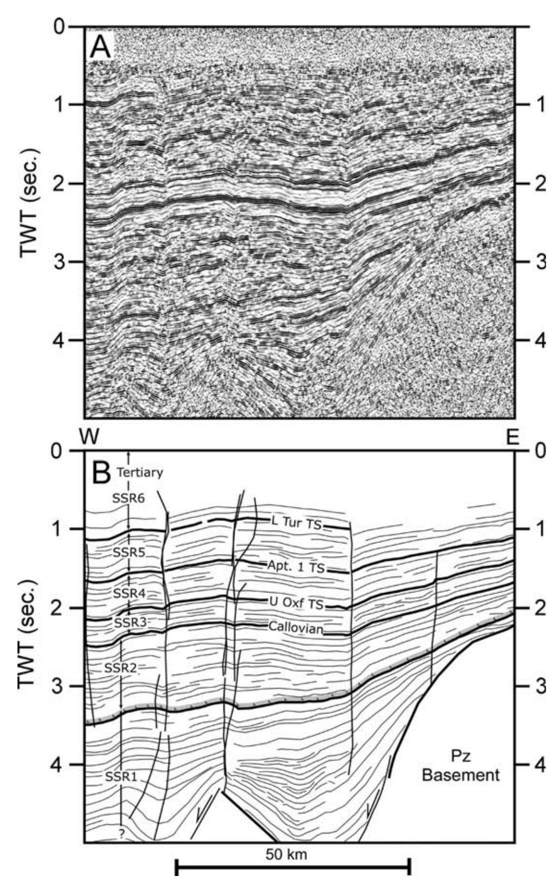

Fig. 24. Details of the regional seismic profile 31. (A) Un-interpreted seismic section, (B) Line drawing. See Fig. 9 for location.

The maximum tectonic deformation took place in the northern and south east areas of the Basin, whereas the rest of the Basin was subject to gradual subsidence (Shatski et al., 1996). This compressional event resulted in the reactivation of all earlier developed structures.

4.4. Mesozoic and tertiary structural evolution

Inspection of the regional seismic profiles and selected line drawings, despite their large vertical exaggeration, makes it apparent that all structures of the West Siberian Basin are very gentle with dips that do not exceed a few degrees. However, the great vertical exaggeration of the seismic profiles does facilitate the recognition of structures and reveals some important aspects of the deformation.

Immediately below the calibrated, but also partially inferred basalt reflector, the seismic data illuminate some subtle depressed structures. These minor depressions have been discussed earlier (Figs. 17 and 18). The exception occurs in the Pur-Taz area where there is convincing evidence for a pre-250 Ma rifting event; see profiles 27 and 31 (Figs. 8, 9, 24 and 25). Unfortunately, the seismic profiles do not extend below 5 s of two-way-time, and the deepest well (SG6) penetrated about 1100 m of ~250 Ma basalts at 4 s (see Fig. 12). The volcanics associated with the rifting event may have been deposited on a topographically rugged surface. Moreover, it is also evident from Fig. 25 that the paleo-high separating the two half-grabens was reactivated in the post-Turonian, probably Tertiary period.

Comparing regional profiles, a significant increase in the SSR2 unit thickness is evident toward the northeast, i.e. the Pur-Taz area. This is particularly dramatic when comparing profile 19 with profiles 27 and 31 (Figs. 8 and 9). The increased subsidence rate may well be related to lithospheric cooling after the ~250 basalt event and graben formation. Nonetheless, it is noted that this increased subsidence is limited to the north-northeastern sector of the basin.

Peterson and Clarke (1991) show wedging and truncation of much of the Mesozoic section towards the eastern Basin margin, suggesting an active uplift of the East Siberian Platform. This movement presumably began during the upper Jurassic, if not earlier (Figs. 15 and 16), as witnessed by the spectacular progradation of unit SSR4 (see Figs. 7–9, 20 and 22). The eastern provenance of the Cretaceous sandstone reservoirs further illustrates a continued uplift of the East Siberian Platform beginning in the Late Jurassic. Mesozoic outcrops in the southeast and northeast are the result of this uplift (Fig. 1).

The western margin of the basin is not covered by the available seismic profiles as the data do not extend up to the

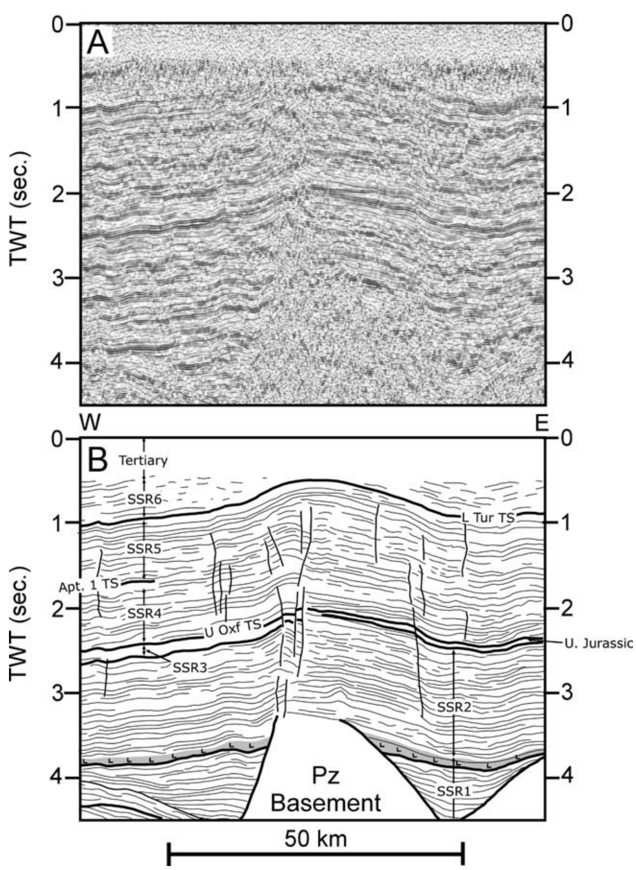

Fig. 25. Details of the regional seismic profile 27. (A) Un-interpreted seismic section. (B) Line drawing. See Fig. 8 for location.

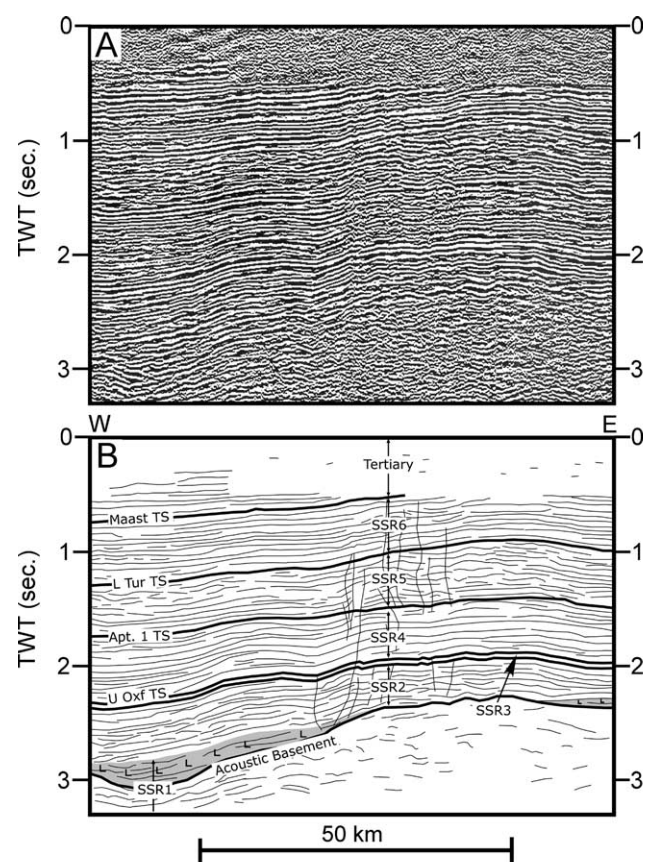

Fig. 26. Details of the regional seismic profile 13. (A) Un-interpreted seismic section. (B) Line drawing. See Fig. 8 for location.

Ural Mountains. It is believed that the Urals were uplifted during the Mesozoic and Tertiary, as suggested by Mesozoic outcrops along the eastern flank of the Central Ural Mountains and by eastward progradation of unit SSR4 on profile 19 (Figs. 8 and 23). However, more data are needed to further illustrate this assertion.

Another interesting aspect of the West Siberian Basin is the existence of Tertiary structures, many of which contain hydrocarbon accumulations (Fig. 3). These structures appear to be compressional and/or transpressional in origin, and are well shown by Figs. 7–9. The long-axis orientation of positive structures varies throughout the West Siberian Basin (Kontorovich et al., 1975), which could be a result of changes in regional stress field. Changes in stress field are common to cratons (Ziegler et al., 1998, 1995; Nikishin et al., 1996). The most recent regional tectonic event observed in the West Siberian Basin took place in the Tertiary (presumably the Oligocene) and could be a product of intra-plate stress created by a Tertiary collision of the Indian Plate with Eurasia. Many processes can be responsible for build-up of 'intraplate stresses'; however, it has been suggested by Ziegler et al. (1998) that 'stress related to collisional plate coupling appears to be responsible for the development of the most important compressional intraplate structures'. Transmittal of a horizontal compressional stress over large distances (up to ±1600 km) has been observed in cratons and is believed to be widespread (e.g. Ziegler et al., 1998, 1995). The distance between the center of the West Siberian Basin and India collision front is about 2400 km, which exceeds the ±1600 km estimate. In spite of this, authors believe that potential ambiguity associated with the ±1600 km estimate is large enough to still consider an Indian Plate collision with Eurasia as a possible source of intra-plate stress build-up in the West Siberian Basin.

Other products of intra-plate stress in the West Siberian Basin are widespread sub-vertical faults and inversion structures (see seismic profiles R1, 27, and 4841; Figs. 7–9, and Figs. 25–28). While intra-plate inversions and fault reactivation structures have been observed in many cratons (Ziegler et al., 1998, 1995), sub-vertical faults observed in the West Siberian Basin are unique because of their

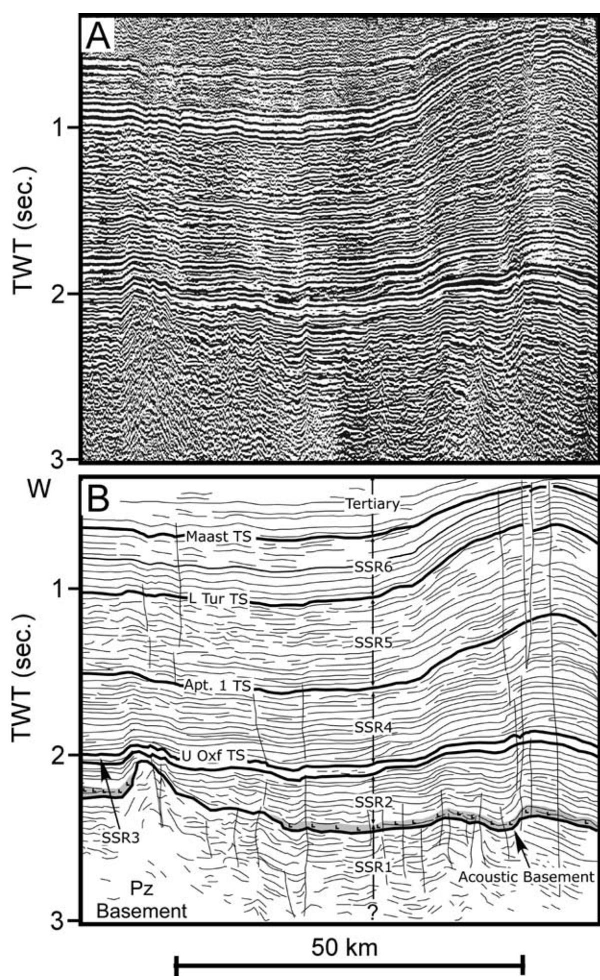

Fig. 27. Details of the regional seismic profile R1. (A) Un-interpreted seismic section. (B) Line drawing. See Fig. 7 for location.

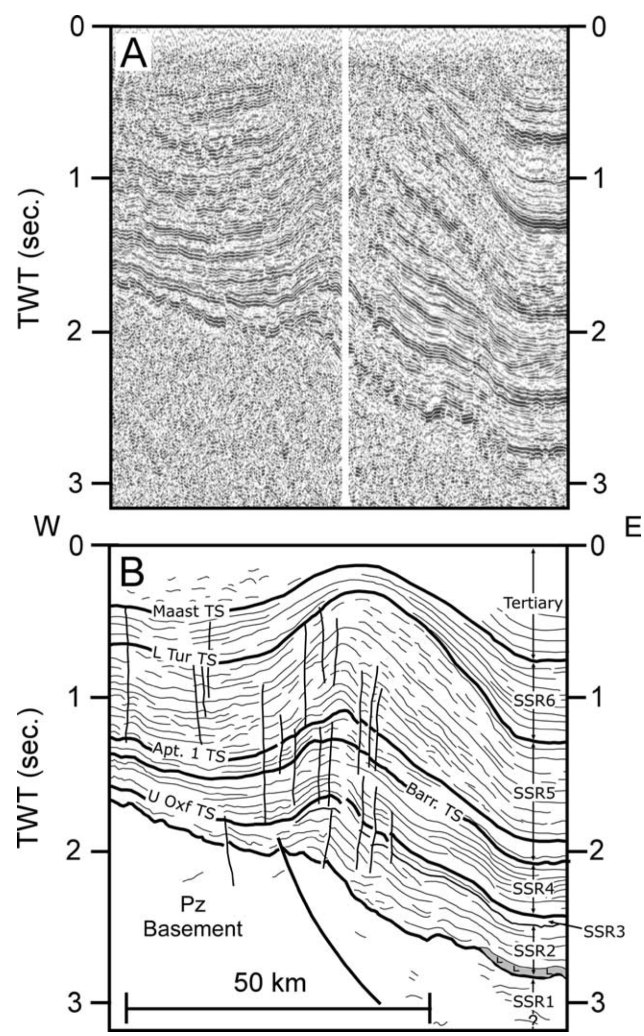

Fig. 28. Details of the regional seismic profile 27 (A) Un-interpreted seismic section. (B) Line drawing. See Fig. 8 for location.

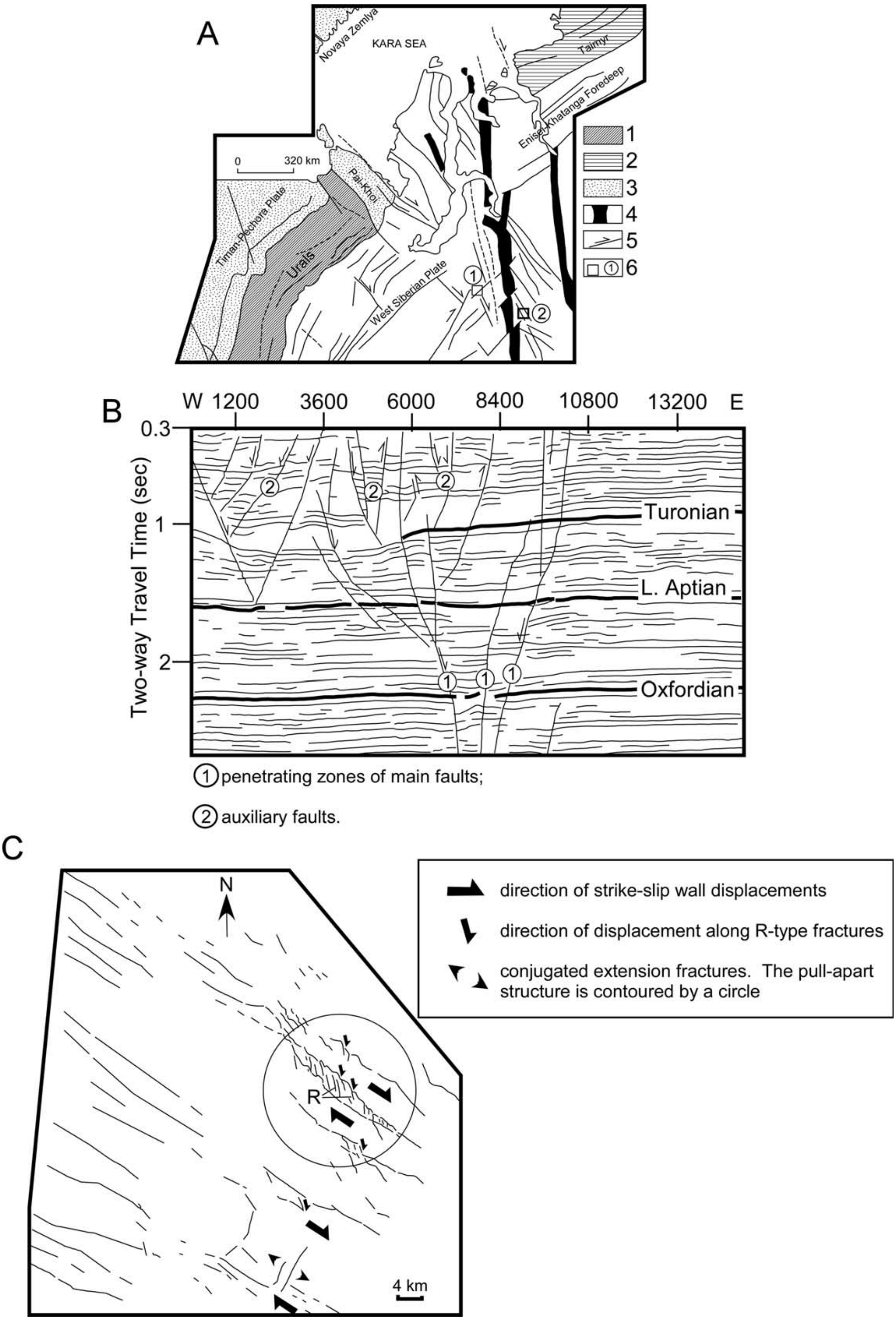

Fig. 29. (A) Tectonic zones of the basement of West Siberian Basin. Legend: 1- Hercynides of the Urals; 2 - Hercynides and Early Kimmerides of the Taimyr region; 3 - Early Kimmerides of Pai-Khoi and Novaya Zemlya. Basement structures: 4 -Triassic rifts, 5 - faults and their kinematics. 6 - study fields: (1) Severo-Komsomol'skii; (2) Kharampur. (B) Line drawing of the seismic reflection profile across Severo-Komsomol'skii field (see A for location of Severo-Komsomol'skii field). Arrows indicate the direction of movement in the section plane. (C) Map of Kharamput field (2) generated based on 3-D seismic data (for location see A). Diagram illustrates the assemblage of dextral faults (A, B and C were redrawn from Belyakov et al., 2000).

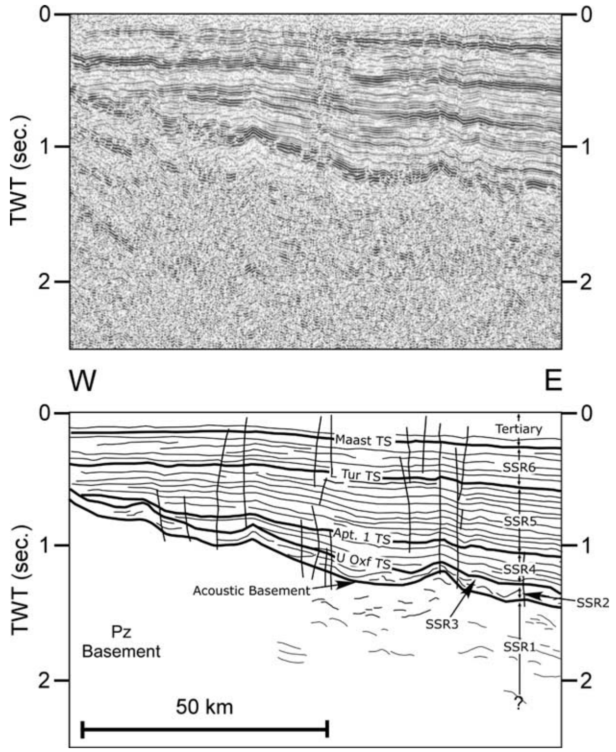

Fig. 30. Details of the regional seismic profile 6. (A) Un-interpreted seismic section. (B) Line drawing. See Fig. 7 for location.

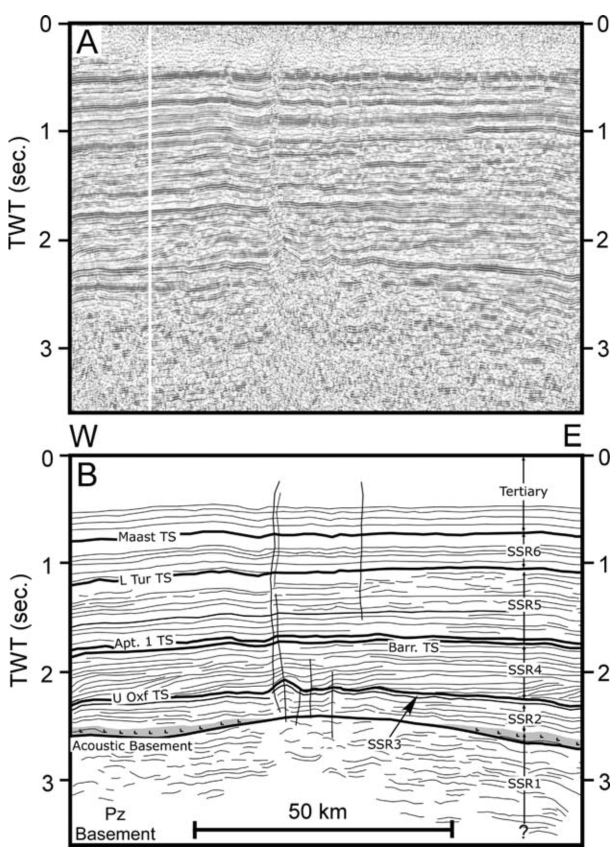

Fig. 31. Details of the regional seismic profile 6. (A) Un-interpreted seismic section. (B) Line drawing. See Fig. 7 for location.

geometries and abundance. The limited coverage offered by the profiles available does not permit to determine the strike of these faults, though Belyakov et al. (2000) conducted detailed mapping of faults using 3-D seismic dataset in the Pur-Taz area of the West Siberian Basin. He recognized and mapped the Mesozoic–Cenozoic strike-slip faults in the Pur-Taz part of the basin and determined NW-SE direction of strike-slip deformation (Fig. 29(A)–(C)). The sub-vertical faults appear to have been initiated during the Triassic–Middle Jurassic deformation period and were reactivated during the Tertiary tectonic event.

The role of more subtle paleostructures in West Siberia remains somewhat elusive. To begin with, it is difficult to differentiate subtle basement structures from paleomorphology (Figs. 30 and 31). The deep structure in the left portion of Fig. 27 shows significant deformation affecting units SSR2–SSR4; however, this structure does not seem to propagate into the Upper Cretaceous section. Thus, a good case can be made for older basement structures (paleo relief) and draping of sediments over them. Such structures may be desirable exploration targets; therefore, a more detailed documentation of paleostructures may be needed.

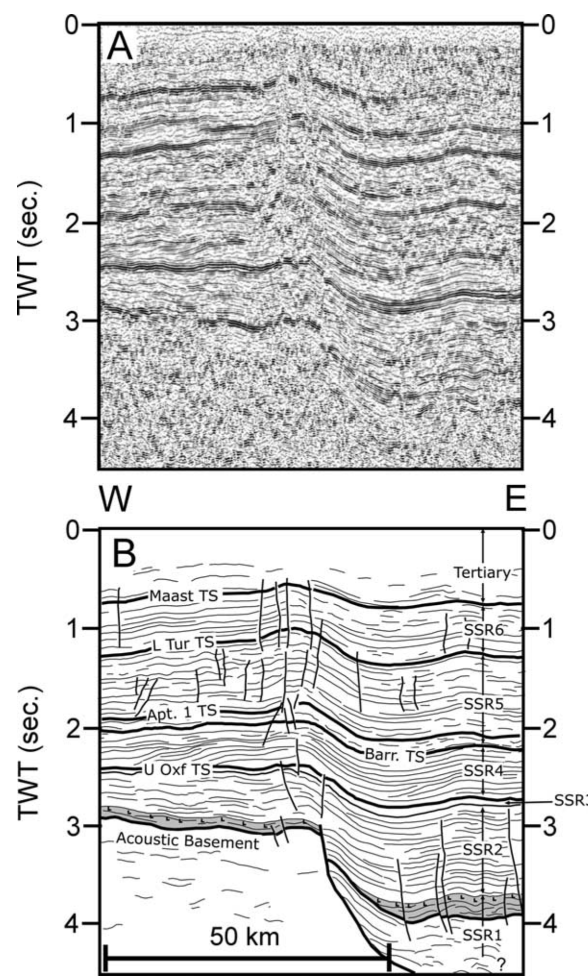

Fig. 32. Details of the regional seismic profile 27. (A) Un-interpreted seismic section. (B) Line drawing. See Fig. 8 for location.

An unusual type of fault re-activation is captured on Fig. 32, and it demonstrates that a normal fault associated with considerable thickening of the SSR2 unit, was reactivated in a transpressional mode to form a gentle Tertiary anticline. This interpretation can be compared to that shown in Figs. 13 and 28, which reveal similar, basement-involved transpressional structures.

5. Summary and conclusions

A number of fundamental questions regarding the origin and early evolution of the West Siberian Basin remain unresolved. One of the main controversial issues is related to the identification of the elements participating in the collision that ultimately formed the basement of West Siberian Basin. The basement consists of Baikalian (Late Precambrian), Caledonian (Cambrian–Silurian), and Variscan (Silurian–Permian age) fold systems that, prior to the collision, were volcanic arc complexes and some platform blocks. A model for the formation of the basement of the West Siberian Basin was introduced by Sengor and Natal'in (1996). They proposed a Late Permian collision of the Russian Platform, the East Siberian Platform, and the Kipchak Arc Complex. One of the most prominent products of the Upper Paleozoic collision is the Ural Mountains, which extend from the Aral Sea to Novaya Zemlya. The Urals are considered to be a key in understanding of Paleozoic plate tectonics.

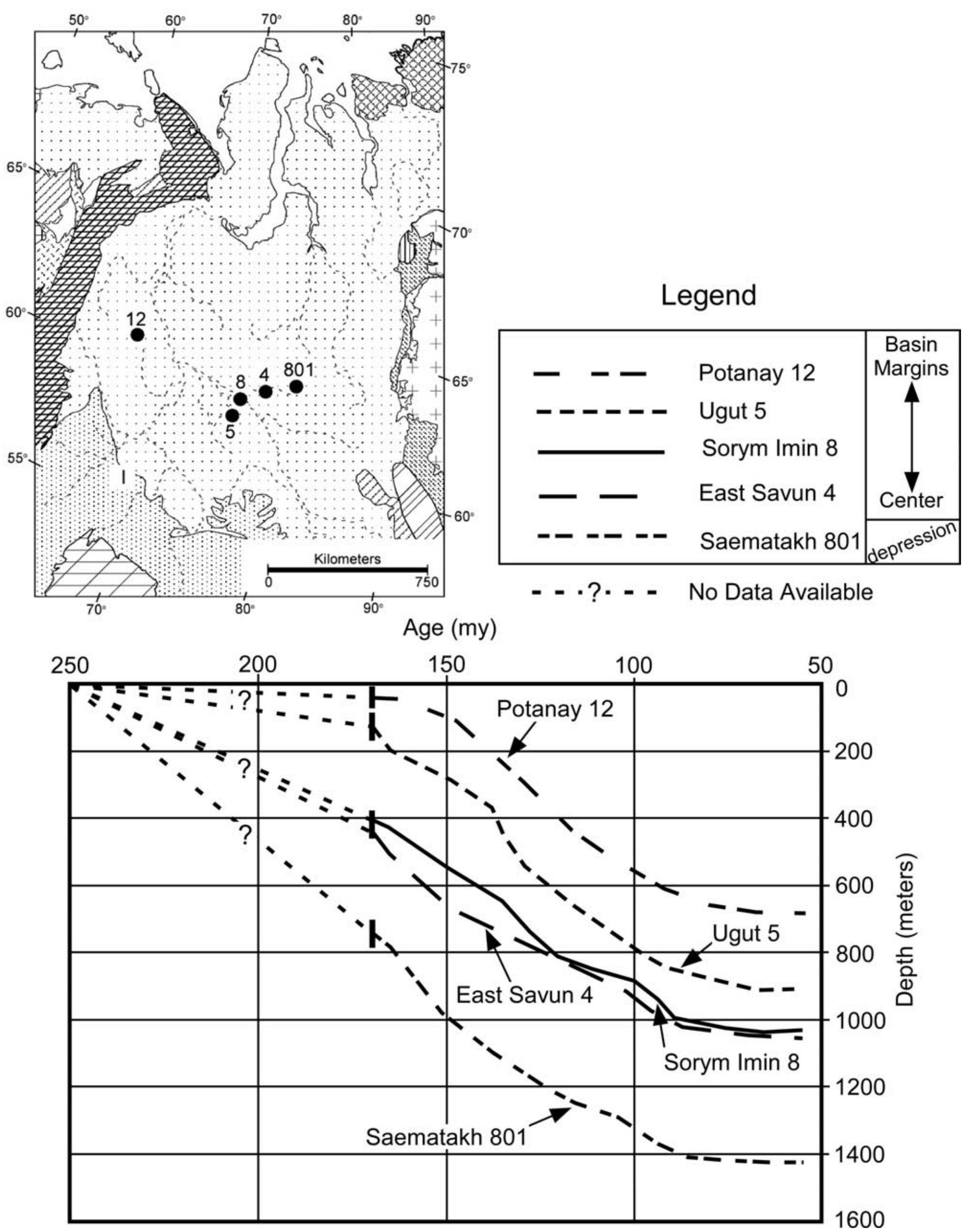

Fig. 33. Variations in tectonic basin subsidence. Tectonic subsidence is higher in the central part of the basin and decreases towards the basin margins. The maximum tectonic subsidence is observed within depression (well Saematakh 801). Subsidence of the Basin was modeled using *BasinWorks* software.

Close investigation of 2-D seismic data tend to suggest that the Permian graben system in the West Siberian Basin is limited to tectonic Zone 1 (Pur-Taz region and Kara Sea). The basin-wide rift system postulated by Surkov and Zhero (1981) and Surkov and Zhero (in Kontorovich et al., 1975) is not supported by the interpretation of regional seismic profiles. Formation of the grabens in the Kara Sea could have occurred simultaneously with Pur-Taz grabens in the West Siberian Basin.

Late Permian and, perhaps, early Triassic evolution of the basin is associated with the development of the Siberian flood basalts and intrusives. The spatial distribution of Siberian basalts is vast, covering the West Siberian basin, East Siberian platform, Yenisey–Khatanga trough, appearing to extend into the Kara and Barents seas (Shipilov and Tarasov, 1998) as well as other localities in Eurasia (Nikishin et al., 2002). This volcanism may be responsible for a spectacular mass extinction that occurred around the Permian-Triassic period (e.g Reichow et al., 2002; Nikishin et al., 2002; Sharma, 1997). Flood-basalts are believed to be a product of major short lived mantle plumes developed under Eurasia around ~250 Ma (e.g Nikishin et al., 2002). Although the duration of Late Permian volcanism is still being debated, the authors of this paper concur that all Siberian basalts are short lived events (<1 Ma).

The eruption of volcanics was followed by basin-wide subsidence—a gradual process that continued until the Tertiary compression. Basin-wide subsidence of the West Siberian Basin is a product of ‘thermal re-equilibration of the lithosphere—asthenosphere system’ following Permian plume activities (Zeigler, 2004). Tectonic and total subsidence at several locations in the West Siberian Basin (Figs. 33 and 34) was calculated using backstripping methodology described by Sclater and Christie (1980). Based on backstripping calculations, it is apparent that tectonic subsidence is lower near the basin margins, higher in the central and northern parts of the basin, and highest in the depressions. The same conclusion can be reached by simply observing isopach maps (Fig. 21). It should be noted that the basalts, which filled the shallow basin in the Permian, (and potentially lower Triassic) now occur as deep as 6400 m in the West Siberian Basin as well as on the surface at Tunguska plateau (East Siberian Platform). As a result, the identity of the West Siberian Basin and its separate development from the Tunguska depression occurred well after the Permian. The reason for the uplift on the basin flanks and subsidence in the basin is likely related to both Triassic tectonism and mantle plume activity associated with widespread basalt floods. Relative buoyancy of the Archean and early Proterozoic mantle (Artemieva and Mooney, 2001) may be another factor that prevented the East Siberian Platform from subsidence.

The post-volcanic stratigraphic section in the West Siberian Basin was subdivided into seven structural-stratigraphic regimes (SSR). A more detailed interpretation was achieved by using transgressive surfaces for the regional

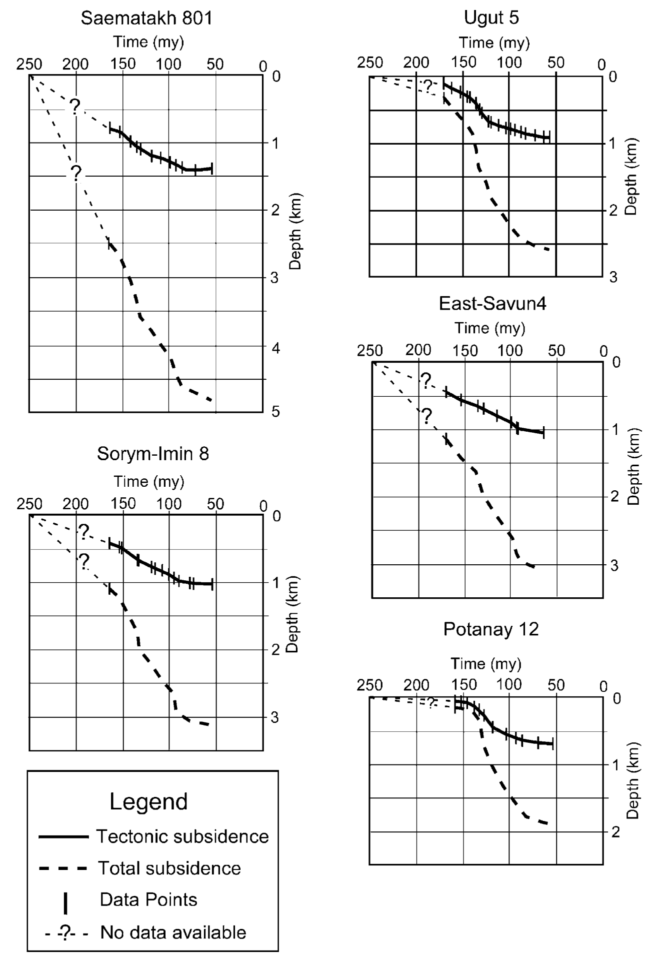

Fig. 34. Curves of tectonic and total subsidence calculated using *BasinWorks* software for the wells located along the regional seismic profile 6. Between Permian basalts (~250 my) and Tithonian flooding (~148 my) no reliable control points for the subsidence modeling exists. No control points exist for the deposits younger than 54.8 my.

sequence stratigraphic correlation. The stratigraphic section was subdivided into transgressive–regressive composite sequences and primary sequences. Thus, the Callovian–Eocene interval was subdivided into one 1st, four 2nd and sixteen 3rd order transgressive–regressive cycles based on their particular physical characteristics. The physical characteristics of any unit are typically interpreted from the seismic data and calibrated to well-logs. Therefore, the definition of ‘order of cycles’ is a matter of seismic resolution.

The relative effect of tectonics and eustasy on the stratigraphic architecture can be readily resolved. Eustasy as a global phenomenon produces consistent effects over the entire basin for a given time, whereas tectonics can exert either local or regional control on a basin. Overall, the basin-wide 2nd order and 3rd order cycles were mostly influenced by eustasy. Tectonic influence is obvious on the western basin margin (evident by the updip convergence of strata), and would likely be observed on the eastern margin where data is limited. During basin evolution, the development of overall accommodation gradually decreases, possibly suggesting a degree of thermal control on the subsidence that may have been initiated by Permian mantle plumes activity. The regional sequence architecture is locally modified by the developing structures.

Significant, presumably early Oligocene, transpressional deformation affected most of the West Siberian Basin (Figs. 7–9). This tectonic event underlies the (1) development of intrabasinal uplifts; (2) reactivation of basement faults and development of inversion structures; (3) uplift of broad anticlinal structures, many of which are associated with deeply buried basinal fault blocks; (4) development/reactivation of an array of subvertical faults and positive flower structures; (5) inversion of half grabens. It is tempting and plausible to explain the Tertiary deformation by intra-plate stress caused by the collision of India with Eurasia; however, the temporal and spatial resolution of the data limits this idea to the realm of speculation.

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