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A mantle plume origin for the Siberian traps: uplift and extension in the West Siberian Basin, Russia

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Abstract

The West Siberian Basin (WSB) records a detailed history of Permo-Triassic rifting, extension and volcanism, followed by Mesozoic and Cenozoic sedimentation in a thermally subsiding basin. Sedimentary deposits of Permian age are absent from much of the basin, suggesting that large areas of the nascent basin were elevated and exposed at that time. Industrial seismic and well log data from the basin have enabled extension and subsidence modelling of parts of the basin. Crustal extension (β) factors are calculated to be in excess of 1.6 in the northern part of the basin across the deep Urengoy graben. 1-D backstripping of the Triassic to Cenozoic sedimentary sequences in this region indicates a period of delayed subsidence during the early Mesozoic. The combination of elevation, rifting and volcanism is consistent with sublithospheric support, such as a hot mantle plume.

This interpretation accords with the geochemical data for basalts from the Siberian Traps and the West Siberian Basin, which are considered to be part of the same large igneous province. Whilst early suites from Noril'sk indicate moderate pressures of melting (mostly within the garnet stability field), later suites (and those from the West Siberian Basin) indicate shallow average depths of melting. The main region of magma production was therefore beneath the relatively thin (ca. 50–100 km) lithosphere of the basin, and not the craton on which the present-day exposure of the Traps occurs. The indicated uplift, widespread occurrence of basalts, and short duration of the volcanic province as a whole are entirely consistent with published models involving a mantle plume. The main argument against the plume model, namely lack of any associated uplift, appears to be untenable.

Keywords: Mantle plume; Siberian Traps, large igneous provinces; Flood basalts; West Siberian Basin

1. Introduction

The Siberian Traps are the largest known Phanerozoic continental flood basalt province, and coincide with the largest known mass extinction event at the end of the Permian Period, ~250 million years ago. Yet, like their oceanic equivalent the Ontong Java Plateau, the world's largest oceanic plateau, there is uncertainty about the mechanism by which the Traps were formed. The observation that large volumes of basalt were erupted in a geologically short period of time has led many workers to suggest that the Traps were formed by melting within a hot mantle plume

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(Morgan, 1971; White and McKenzie, 1989; Arndt et al., 1993), perhaps an impacting 'start up' plume (Richards et al., 1989; Campbell and Griffiths, 1990), but the apparent absence of uplift preceding or accompanying the eruption of the basalts led Czamanske et al. (1998) to propose that a buoyant mantle plume could not have been involved. Furthermore, unlike many other flood basalt provinces, there is no obvious succeeding plume 'trail' leading to a presently active hotspot (e.g., the Chagos-Laccadive Islands trailing from the Deccan Traps to the volcanically active island of Réunion). It is unclear, therefore, whether any form of mantle hotspot persisted after the formation of the Traps. These apparent contradictions have spawned a series of alternative models to explain the formation of the Traps, including enhanced mantle convection at the edge of the Siberian Craton (Czamanske et al., 1998), lithosphere delamination (Tanton and Hager, 2000), melting of deep cratonic lithosphere (Zorin and Vladimirov, 1989), and a bolide impact (Jones et al., 2002).

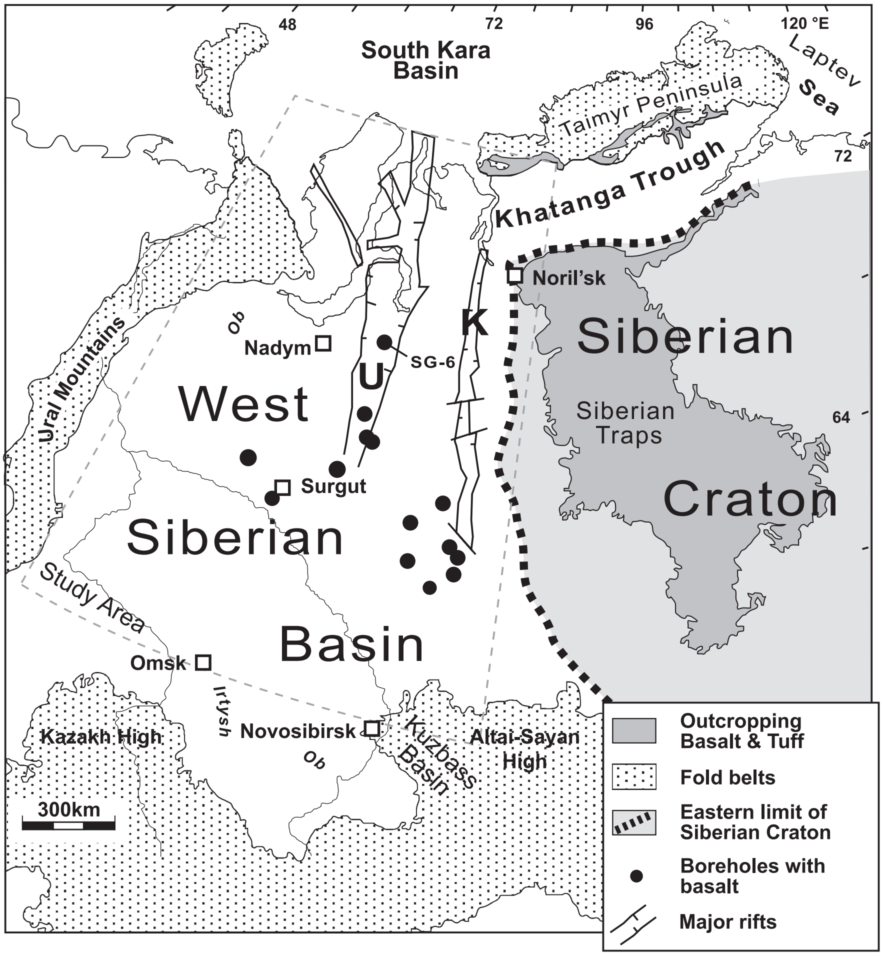

Fig. 1. Map of the West Siberian Basin (WSB) and adjacent regions. Shown are the following: (i) the limit of the Siberian Craton. Lithospheric thickness decreases from approximately 300 km (cratonic) to less than 150 km (non-cratonic) at this boundary (e.g., Zhang and Tanimoto, 1993; Artemieva and Mooney, 2001). (ii) The major subcropping rifts [Urengoy (U) and Khudosey (K)] in the WSB, modified after Al'Mukhamedov et al. (1999), and incorporating the results of this study (see Figs. 3 and 4). (iii) The outcrop of the Siberian Traps. (iv) The locations of boreholes which provided samples for Reichow et al. (2005). A more complete set of borehole locations is given in Fig. 2. (v) Our study area is outlined by the dashed line, and which corresponds to Figs. 2 and 3.

In this contribution, we review the geology of the Traps within the context of the West Siberian Basin (WSB) (Fig. 1). Using industry seismic and borehole data, we have undertaken a study of the rifting and subsidence history of this Mesozoic–Cenozoic sedimentary basin, one of the world's largest. A widespread subcrop of Permo-Triassic volcanic rocks occurs beneath the WSB, perhaps as large in areal extent as the Traps on the Siberian Craton to the east (e.g., Al'Mukhamedov et al., 1999; Reichow et al., 2002, 2005; Medvedev et al., 2003). Crustal extension and rifting are recorded in the faulted structure of the basement and overlying Triassic sedimentary sequences. The absence of a widespread sedimentary record for the Permian suggests that uplift, perhaps plume driven, occurred at this time in the WSB. This was followed by a prolonged period of thermal subsidence throughout the Mesozoic and Cenozoic. We argue that the bulk of the basaltic magmatism recorded in the WSB and on the Siberian Craton originated beneath the rifting basin, and not beneath the craton.

2. The West Siberian Basin

2.1. Broad physiography and structure

The West Siberian Basin is one of the world's largest flatlands, a vast area stretching from the Ural Mountains in the west to the Siberian Craton in the east (Fig. 1). The northern end of the basin includes the South Kara Basin and Khatanga Trough, and in the south, the WSB is bounded by the Kazakh and Altai-Sayan Highs. The WSB and its contiguous basins cover an area of approximately 3.5 million km^2, and are noted for their deposits of hydrocarbons including some of the world's largest natural gas fields (Peterson and Clarke, 1991).

The WSB contains Mesozoic and Cenozoic sedimentary rocks deposited on a rifted Proterozoic and Palaeozoic basement. The main axis of the basin trends approximately north–south, paralleling the geometry of the rifted basement surface. The basement surface also has a strong regional northward tilt, with the depth-to-basement increasing to more than 15 km in the northern Pur-Gedan Basin (which contains the large Urengoy and Khudosey rifts) and beneath the Kara Sea (Pavlenkova et al., 2002). Depth-to-Moho data show crustal thinning along the central axis of the basin; along the basin flanks, the seismic Moho is located at approximately 46 km depth, shallowing to about 38 km beneath the central part of the basin near Surgut (ca. 62°N), and to less than 34 km further north beneath the Urengoy rift (Aplonov, 1995).

Based on geophysical surveys and borehole sampling, the basement is a collage of rock types ranging in age from Proterozoic to Upper Palaeozoic (e.g., Peterson and Clarke, 1991; Aplonov, 1988, 1995; Sengör et al., 1993; Bochkarev et al., 2003). It appears to represent an amalgamation of terrane blocks, comprising fragments of island arcs, microcontinents, and relict ocean basins. Unlike the adjacent Siberian Craton, no Archaean rocks have been recovered from the WSB basement. In terms of lithology, age and structure, the basement of the WSB more closely resembles the Altaid orogenic collage exposed at the southern margins of the basin, rather than the far older Siberian and East European cratons (Sengör et al., 1993). Thermal modelling and global seismic tomography indicate that the lithosphere beneath the WSB is much thinner (100–150 km) than beneath the Siberian Craton (>300 km) (Zhang and Tanimoto, 1993; Artemieva and Mooney, 2001).

2.2. Mesozoic and Cenozoic sedimentation

The following account is largely summarised from the detailed review by Peterson and Clarke (1991), augmented by more recent findings. The WSB was a broad, shallow inland sea throughout most of the Mesozoic and Cenozoic. The basin fill is almost entirely clastic, and was deposited in three major sedimentary megacycles (Triassic–Aptian; Aptian–Oligocene; and Oligocene–Quaternary), which represent transgressive–regressive episodes. Continental sedimentation dominates the lower units of each megacycle, grading upwards into marine and finally near-shore sedimentation at the top.

Devyatov et al. (1995) indicate that large areas of the nascent WSB were emergent in the late Permian and early Triassic, with elevations exceeding 2 km in the southern and western parts. During this period, the region underwent limited extension, forming a series of asymmetric horst and graben structures with roughly north–south trends. The horsts and grabens are distributed across the basin, especially in the central area around Surgut (ca. 62°N), although in the north the rifting is localised into two dominant structures, the Urengoy and Khudosey grabens (Fig. 1), which have vertical displacements along their margins of up to 5 km (Surkov and Zhero, 1981). These grabens are partially filled with basaltic rocks, overlain by Triassic sedimentary rocks. Lower to Middle Triassic sedimentation was predominantly continental, with the grabens acting as major depocentres for conglomerates, sandstones, and volcanic rocks (thicknesses in the graben may exceed 3 km). Triassic marine sedimentary rocks (part of the Tampei Series) are mixed with sediments of continental origin in the northern part of the WSB, where the total thickness exceeds 6 km. The precise timing of the onset of rifting is unknown, but is thought to be late Permian or early Triassic, approximately coeval with the basaltic volcanism (e.g., Kontorovich et al., 1975). Rifting continued into at least the Triassic, because many of the grabens—especially those in the northern part of the basin—contain sedimentary and volcanic deposits of this age deposited against large growth faults.

The WSB began to subside in the Early Jurassic and continued to subside throughout the Cretaceous and Paleogene. The greatest subsidence was in the north, where the extension was largest. In the northern region of the basin, the Lower Jurassic sediments were initially mainly lacustrine and continental, and rested directly on the Triassic Tampei Series (Peterson and Clarke, 1991). Early and Middle Jurassic marine transgressions migrated southwards along the subsiding rift axes, before spreading out to cover the previously emergent Proterozoic and Palaeozoic basement on the flanks of the rifts and on the horsts. The first major marine transgression occurred in the Middle Jurassic, and reached approximately 64°N. Bounding this developing inland sea were coastal plains, and these were eventually covered during widespread Upper Jurassic marine transgressions, which reached as far south as 54°N. The bituminous Upper Jurassic Bazhenov Formation was deposited over much of the WSB during a period starved of coarse clastic sedimentation. During the Cretaceous and Cenozoic, the WSB continued to subside, undergoing a series of marine transgressions and regressions. The total Jurassic, Cretaceous and Palaeogene sediment fill ranges in thickness from about 5500 m in the northern part of the basin, to about 3000 m in the central part (Peterson and Clarke, 1991).

3. Methodology

We have obtained access to approximately 25,000 km of industrial 2-D seismic reflection lines, and well log data, from JEBCO Seismic (UK). The full suite of seismic lines loaned by JEBCO is shown on Fig. 2, although not all of these have been interpreted for this study. The majority of the lines extend to approximately 5 s two-way travel time (twtt), which corresponds to a depth of approximately 8 km. Interpretation of this extensive grid of commercial 2-D seismic reflection profiles has enabled the broad structure of the West Siberian Basin to be determined. This was achieved by mapping two seismic marker horizons, constrained using well log data, over most of the seismic grid. The first of these, the top of basement, was identified from the well data and in the seismic data as the base of the reflective section (Fig. 3). The second major reflector was the Upper Jurassic Bazhenov Formation, which mostly comprises a bituminous mudstone.

We have obtained lithological data logs for a set of five industrial wells, which have enabled us to evaluate the subsidence history of these parts of the basin. Our companion paper (Reichow et al., 2005) describes the geochemistry of basalts from 12 industrial boreholes located in the WSB, and their results are integrated into this study. Basalts dated by $^{40}Ar/^{39}Ar$ methods are Permo-Triassic in age (ca. 251 Ma) (Reichow et al., 2002).

4. Basement faulting

The basement surface of the WSB is irregular and can be shown to be cut by numerous normal faults, some with a displacement of more than 1 s two-way travel time (twtt). Footwall crests show little evidence of rounding off (erosion) and appear to be well preserved beneath a thick layer of near horizontally bedded early Jurassic sedimentary rocks. There is no evidence of faults penetrating into the sediments deposited on top of the footwall blocks. Interpretation of the seismic data and composite cross-sections derived from Russian well data suggests that basalts penetrated by drilling are preserved within the half-grabens bounded by these faults. The half-graben contain packages of reflectors, which diverge toward the interpreted normal faults, indicating that some of the faults were active during sedimentation.

In the Urengoy region to the north, the basin is defined by a relatively narrow NNW–SSE-striking graben, the Urengoy rift (Fig. 3). In the axis of this rift, the top of the basement cannot be mapped in the

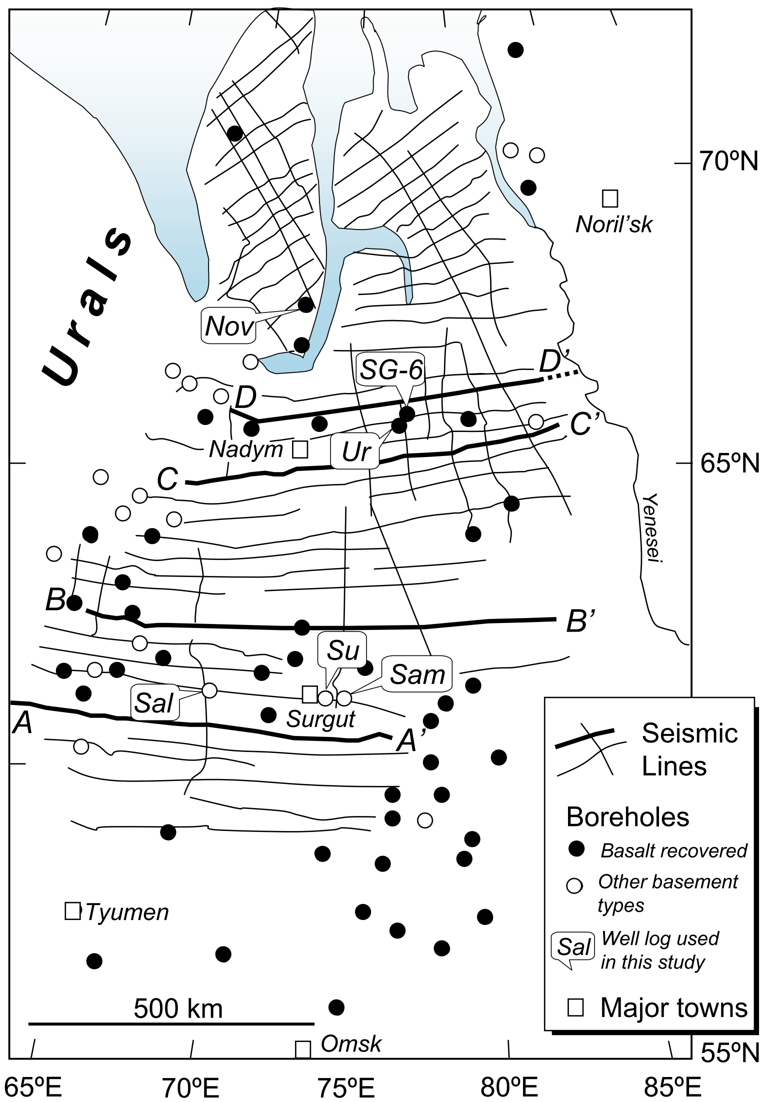

Fig. 2. Map of the West Siberian Basin showing the location of the seismic lines used in this study (labelled seismic lines refer to Fig. 4), and of boreholes which have penetrated basaltic rocks and non-basaltic basement (after Aplonov, 1995). Note that this is far from a complete set of boreholes which have been drilled in this basin (see also Bochkarev et al., 2003). Additional, labelled boreholes were located using data provided by JEBCO Seismic (UK), and these provided well-log data for the subsidence analysis (Nov: Novoporto-130; Ur: Urengoy-414; Sal: Salym-184; Sam: Samotlar-39; Su: Surgut-51). Borehole SG-6 is the superdeep (>7 km) well in the Urengoy rift that penetrated over 1 km of basalt before drilling stopped (Westphal et al., 1998; Nikishin et al., 2002).

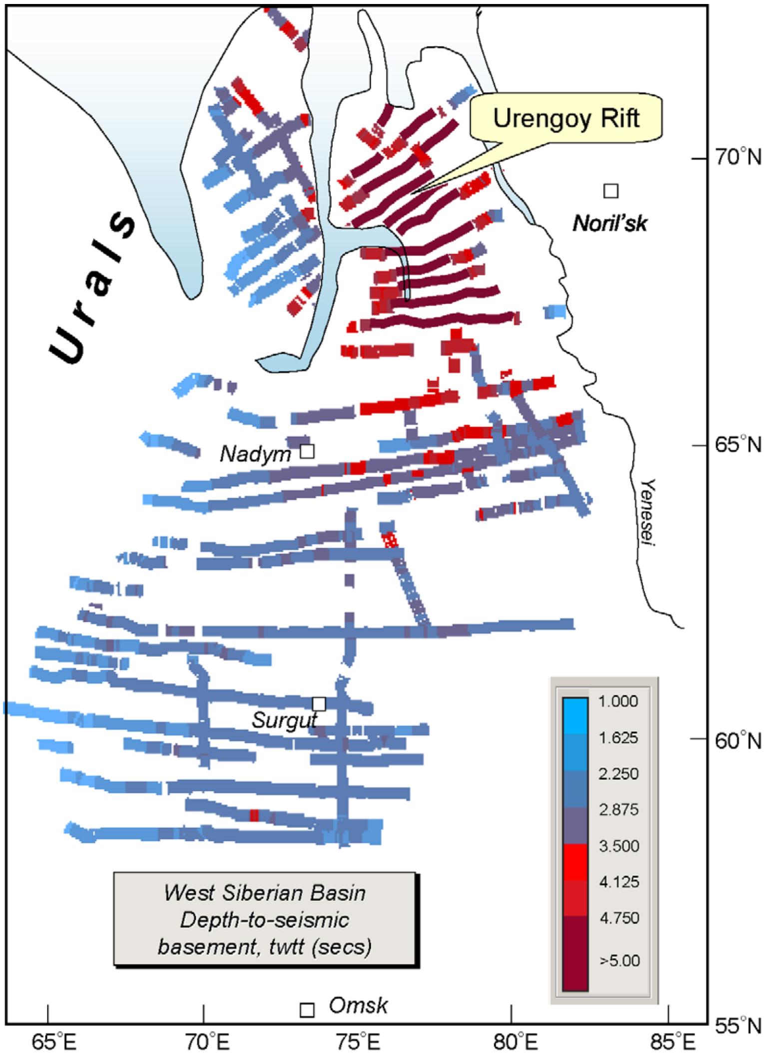

Fig. 3. Depth-to-basement (in seconds two-way travel time) mapped along a subset of seismic lines. Note the general deepening of the WSB towards the north, and the development of a major rift structure, the Urengoy rift, to the north of about 65°N. Further south, faulting of the basin floor appears more widespread.

seismic sections since it lies below the base of the sections (>5 s twtt) north of about 68°N (Fig. 3, and line section D–D′ on Fig. 4). It has been argued that this rift can be traced as far south as Omsk (55°N) (e.g., Aplonov, 1995), but we can find no unequivocal evidence for a discrete rift further south than about 65°N. South of about 65°N latitude, the distribution of faults is more diffuse (e.g., line sections A–A′ and B–B′ on Fig. 4), and the individual displacements are smaller. In the Surgut region (ca. 62°N), some of the graben structures can be traced across adjacent E–W seismic profiles, but many cannot, suggesting that they have limited strike lengths. To the east of the Urengoy rift is the subparallel Khudosey rift, too far to the east to be clearly resolved on our seismic sections.

Above the tops of the footwalls of the faulted top basement, the basin is filled with a monotonous near-horizontally bedded sequence of reflectors. A marker horizon (the Tithonian Bazhenov Formation, a bituminous mudstone) can be located from well data and mapped across most of the basin. This horizon appears unbroken by faulting (the seismic data were

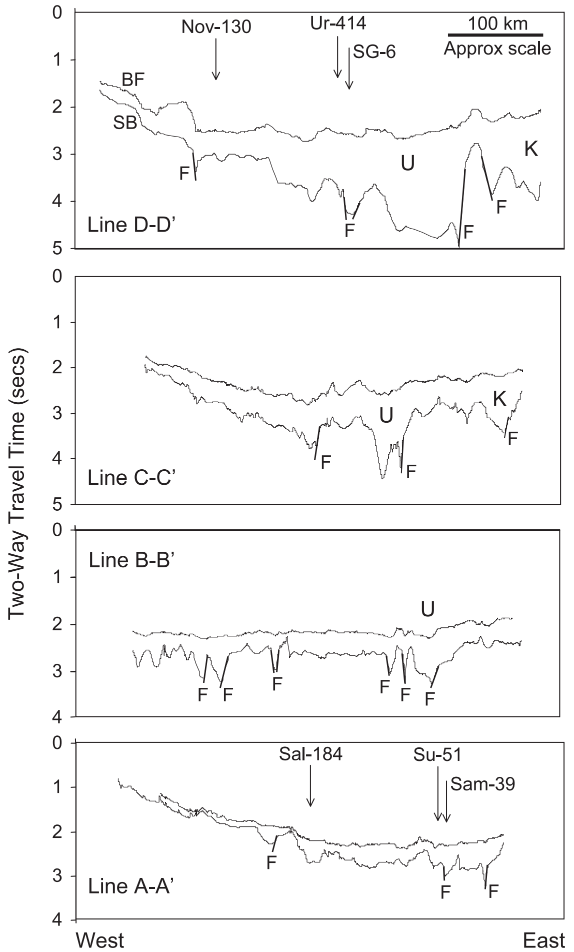

Fig. 4. Depth-to-seismic basement (SB) and to Bazhenov Formation (BF) (in seconds two-way travel time) for four east–west seismic profiles across the WSB. The two southernmost profiles (A–A′ and B′–B: locations are given on Fig. 4) show a relatively smooth basement reflector, albeit one with numerous small half-grabens and full grabens. The more northerly profiles (C–C′ and D–D′) show the development of major rift structures, the Urengoy (U) and Khudosey (K) rifts. The Urengoy rift has the appearance of a gigantic half-graben which may extend as far south as Omsk (e.g., Aplonov, 1995), although the Urengoy rift structure is not clear on profiles B–B′ and A–A′. Note that the Bazhenov Formation shows much smaller depth variation than the basement surface, consistent with cessation of faulting in the early Jurassic or late Triassic. Where their effects are visible in the seismic sections, faults (F) are shown on the profiles. All profiles have a vertical exaggeration of approximately 40.

displayed and interpreted with a 10× vertical exaggeration which would reveal any significant offsets of reflectors) (Fig. 4). Some undulation in the mudstone marker horizon surface is apparent, possibly due to late Cenozoic compression. However, a plot of twtt to the mudstone and top basement against distance along a seismic line crossing the width of the basin (Fig. 4) shows that antiforms in the mudstone are correlated with footwall blocks at basement level, indicating a compaction effect. Immediately above the mudstone, a thick package of prograding clinoforms are observed in the seismic data, but otherwise the sediments are mostly parallel bedded.

5. Extension and subsidence modelling

Peterson and Clarke (1991) determined water depths from the major stratigraphic units within the basin and showed that the surface of the West Siberian Basin remained close to sea level, with sedimentation in either shallow water (<500 m depth), or low-lying marginal areas. When eustatic sea level changes are taken into account, this provides a good control on relative uplift and subsidence across the area of the basin.

If emplacement of the Siberian continental flood basalt province was associated with the ascent and arrival of a mantle plume at the base of the lithosphere, significant surface uplift (of the order of 1 km) would be expected above the head of the plume, decreasing to zero over a radius of approximately 800 km, depending upon the difference in temperature and viscosity between the plume head and surrounding mantle (Griffiths and Campbell, 1991). If present, this uplift could result in a hiatus in deposition and possibly an angular unconformity within the sedimentary succession preserved within the basin. In principle, mapping the basin and producing a water-loaded subsidence curve, corrected for eustatic sea-level change, should reveal any uplift event.

5.1. Extension factors

Mean stretching factors (β) of 1.1 and 1.28 for the Surgut and Urengoy regions, respectively, were obtained by using estimates of depth-to-Moho from seismic refraction profiling (Aplonov, 1995), and measured depths-to-top-basement from seismic depth transects (e.g., Fig. 4). Ratios of crustal thicknesses with respect to the unstretched crust were calculated for two traverses across the central (62°N, profile B–B′ on Fig. 4) and northern (68°N, profile D–D′ on Fig. 4) parts of the basin. The increase in β to the north is consistent with the increase in depth to top basement observed from the seismic (twtt) data (Figs. 3 and 4), and the elevated Moho (Aplonov, 1995). Given that the basin is over 500 km in width, it is unlikely that the crust will have sufficient strength to support the load of the sediments and hence the basin is likely to be in isostatic equilibrium. To verify this, the ratio of the deflection of the top of basement due to the load of the sediments (mean density 2400 kgm^{-3}) with respect to the deflection of the top of the basement if it was in isostatic equilibrium, was obtained (Turcotte and Schubert, 2002). The calculated ratio of 0.98 confirms that the load of the basin fill is weakly supported and that at the present day it is approximately in isostatic equilibrium.

5.2. Subsidence in the West Siberian Basin

Composite logs from wells drilled at five locations were available for this study (Fig. 2), plus published data for the SG-6 superdeep well (Nikishin et al., 2002). All of these wells penetrate basement, denoted on the Russian well logs as undifferentiated Palaeozoic rocks. Two of the wells (Salym-184 and Novoporto-130) record sedimentary rocks of Lower Lias age (ca. 190 Ma), resting on basement. Another two wells (Surgut-51 and Samotlar-39) record sedimentary rocks of middle Jurassic age (ca. 165 Ma) resting directly on basement. Examination of the location of these wells relative to the top basement (Figs. 2–4) shows that they were drilled either at the edges of the basin or on footwall highs, and thus do not record the full sedimentary record of the basin. The fifth well, Urengoy-414, drilled through middle Triassic sedimentary rocks (ca. 240 Ma) into Palaeozoic basement. A sixth well, the SG-6 superdeep well, also from the Urengoy region, drilled into underlying basalt (Nikishin et al., 2002). These latter two wells provide the most complete sequences of sediments known for the West Siberian Basin. Consequently, any evidence of dynamic uplift or thermal support related to a mantle plume should, if present, be preserved in these sedimentary records.

The six wells contain a detailed record of sedimentation in the West Siberian Basin. There are two minor unconformities recorded in the wells at ca. 220 and 160 Ma. Composite logs and interpreted cross sections from other well logs not available to this study record a sequence of shallow marine sandstones and shales for the Jurassic, Cretaceous and Cenozoic periods. Triassic sediments, where present, are predominantly continental but marine incursions in the northern part of the basin indicate that they were deposited close to sea level (Peterson and Clarke, 1991).

The seismic data are broadly interpreted as showing that the West Siberian Basin originated in a rifting event that occurred at around 250 Ma ago, at the time that the Siberian Traps were being emplaced. Although it is not possible to clearly distinguish between basalts and sediments or between basalts and top basement in the seismic data, it is possible to say that the rifting and the emplacement of the basalts are probably synchronous. The maximum duration of this rifting event can be determined from the age of the youngest sediments onlapping the footwalls of the faults. The youngest rocks onlapping basement in the Surgut and Samotlar wells are 165 m.y. old, suggesting a maximum duration of ca. 85 Ma for the rifting event. However, it is likely that the end of rifting predated 165 Ma, with the last onlap occurring as the result of a rise in sea level which began at 170 Ma. Prior to this, water depths were consistently shallow and sedimentation was dominated by shallow water facies (Peterson and Clarke, 1991). The Urengoy-414 well records accumulation of only 1.42 km of sediments for this 85 Ma period which implies that the basin was not subsiding rapidly, as would be expected during active rifting. Much of this deposition can be accounted for as a result of the gradual rise in eustatic sea level which occurred at this time (Haq et al., 1987). The only period of rapid subsidence consistent with active rifting is recorded in the SG-6 well between 250 and 243 Ma (Nikishin et al., 2002).

After 170 Ma, the continuous accumulation of sediments is interpreted as resulting from continuous subsidence of the basin. The absence of faults cutting the sedimentary pile at levels shallower than the basement highs excludes the possibility of a later (post-165 Ma) rifting event. It is therefore argued that any change in the subsidence of the top basement

Table 1
Physical properties used in backstripping

Rock	Compaction coefficient (km^{-1})	Surface porosity (ϕ_0)	Density ($kg\ m^{-3}$)
Siltstone	0.39	0.56	2680
Sandstone	0.27	0.49	2650
Mudstone	0.51	0.63	2720
Clay	0.51	0.63	2720
Calcareous mud	0.71	0.70	2710

must be the result of dynamic processes acting on a long wavelength. The magnitude and rate of change of these dynamic processes can be recovered from a backstripped water-loaded subsidence curve for the top basement.

The composite well logs for the five sets of well data supplied by JEBCO Seismic (UK) were used to calculate water-loaded subsidence curves by back-stripping the well data. Water-loaded subsidence curves (depth to top basement beneath a water-filled basin) correct for varying density of sediment infill, making comparison between different areas of the same basin possible. The curves were calculated using a 1-D backstripping programme based on that in Allen and Allen (1990), modified to include palaeobathymetry and eustatic sea level. Details of lithologies, age ranges and bed thicknesses were taken from the composite well logs. Surface porosities, compaction coefficients and sediment grain densities are given in Table 1, and water depths are given in Table 2. Estimated palaeowaterdepths are from Peterson and Clarke (1991), and eustatic sea level is from Haq et al. (1987). Where palaeowaterdepths were not known, and for the Triassic part of the section, it was assumed that sedimentation kept pace with relative rise and fall in sea levels (i.e., the water depth was zero).

The calculated subsidence curves for the Urengoy-414 well and the SG-6 superdeep well, from Nikishin et al. (2002), reveal the early history of subsidence in the WSB immediately following the rifting associated with the eruption of the basalts (Fig. 5). The SG-6 well shows a steep (assumed to be synrift) curve from 250 to 243 Ma, but the curve then shallows abruptly. The Urengoy-414 well records subsidence from 240 Ma and does not show a steep (synrift?) curve but begins with an almost linear subsidence curve. Both wells show an increase in rate of subsidence at 190 Ma. This is particularly sharp in the case of the Urengoy-414 data. However, as noted above, the seismic data do not show faults cutting Middle Jurassic sediments (ca. 170 Ma), there was no significant increase in water depth, and sedimentation kept pace with rising sea levels, none of which is consistent with an active rifting event at this time.

The Salym and Novoporto wells record subsidence from 190 Ma and the Surgut and Samotlar wells from 165 Ma. These curves all show a broadly exponentially decaying subsidence curve normally associated with thermal subsidence.

Theoretical thermal subsidence curves for an instantaneous (<60 m.y. duration) stretching event with β of 1.28 and 1.62 (estimated as a minimum and a maximum for the Urengoy region, and measured from the ratio of the thickness of unstretched crust to the thickness of the basement locally beneath each well) are plotted against the Urengoy-414 and SG-6 curves in Fig. 6. Both curves begin at 240 Ma, the end of the synrift subsidence phase as determined from the SG-6 well, from the absence of significant post-basalt faulting in the seismic data, and from the sedimentary

Table 2
Estimated water depth and eustatic sea level change through time used in modelling subsidence in the Urengoy-414 well

Age (Ma)	Eustatic sea level (km)	Water depth (km)
239.500	−0.025	0.000
230.000	0.000	0.000
223.400	0.030	0.000
208.000	−0.060	0.000
189.000	0.000	0.000
188.600	0.000	0.000
187.000	−0.010	0.000
178.000	−0.010	0.000
173.500	0.020	0.000
166.100	0.050	0.000
161.300	0.020	0.050
161.000	0.020	0.050
153.000	0.050	0.050
145.600	0.080	0.150
140.700	0.120	0.100
137.500	0.110	0.010
123.400	0.050	0.000
90.400	0.200	0.000
88.500	0.180	0.000
75.800	0.200	0.000
64.100	0.150	0.000
60.000	0.150	0.000
0.000	0.000	0.000

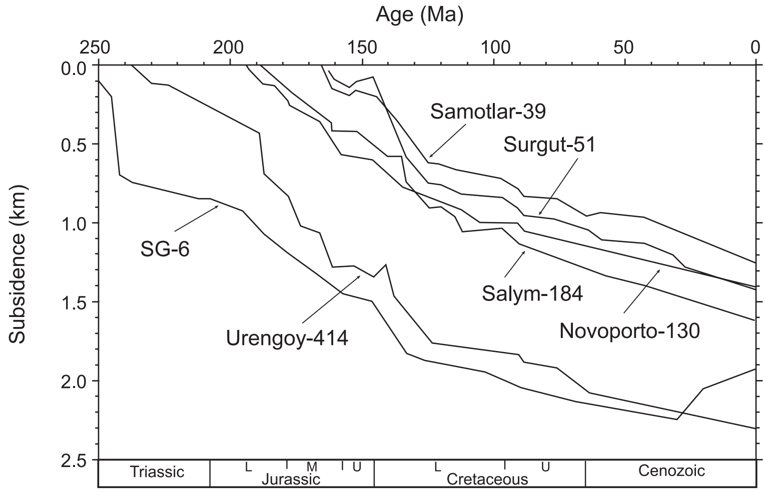

Fig. 5. Graphs of water-loaded subsidence against time derived by backstripping six wells from the WSB (solid lines labelled with well names). Data for SG-6 from Nikishin et al. (2002). Geological time scale from Harland et al. (1990).

record. A comparison of the curves shows that the subsidence during the 240–190 Ma interval in both wells is at a much lower rate than is theoretically predicted from a steady state cooling model for the lithosphere. Between 240 and 190 Ma there is a deficit of ca. 500 m of subsidence in the Urengoy-414 well and ca. 700 m in the SG-6 well for a β of 1.62. After 190 Ma, the rate of subsidence in both wells increases and exceeds that expected from the theoretical model. This discrepancy may be due to an underestimate of the stretching factor at that time. However, if the stretching factor was higher post-190 Ma, then the subsidence rate would have been even higher in the period 240–190 Ma.

5.3. Discussion of extension and subsidence analysis

If rifting had continued after ca. 240 Ma, the subsidence curves would be initially steeper, because thermal subsidence would have accompanied the

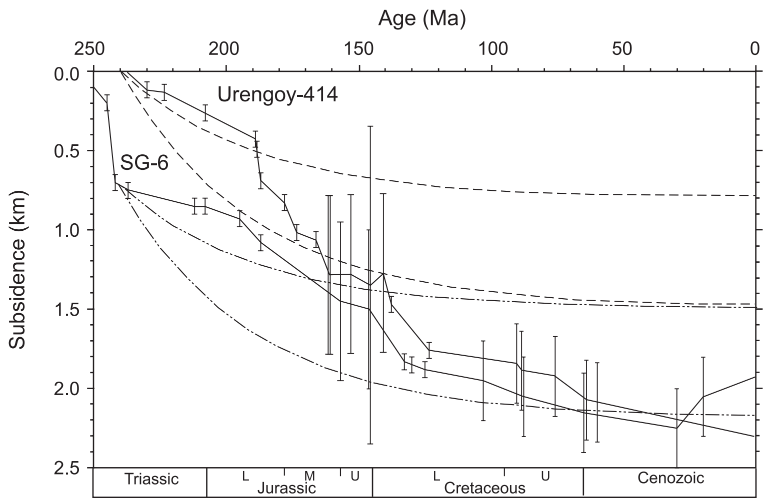

Fig. 6. Water loaded subsidence calculated by backstripping the Urengoy 414 well and SG-6 (Nikishin et al., 2002). Vertical bars are maximum errors in water depth estimated from Peterson and Clarke (1991). The grey curves are theoretical post-rift thermal subsidence for β=1.28 and β=1.62 referenced to the end of rifting and the start of thermal subsidence in each well. Geological time scale from Harland et al. (1990).

rifting (Jarvis and McKenzie, 1980). For the subsidence curve to be shallow requires slower cooling of the upper mantle. Campbell and Griffiths (1990) note that the presence of a mantle plume can result in approximately 1 km of uplift, depending on the mantle potential temperature. The missing subsidence in the Urengoy-414 and SG-6 wells is consistent with the decay of a thermal anomaly due to a mantle plume with an elevated potential temperature.

If we assume that the bulk of the rifting occurred in the late Permian or Triassic, which is consistent with the eruption of basalts at this time, then some form of support of the lithosphere—such as from an active mantle plume—is indicated for the WSB. Extension factors as much as 1.4 (or even 1.6) should have led to major marine incursions, but marine sedimentation does not occur until the late Triassic. Rather, thick (several kilometers) of continental sediments were deposited in the northern rift basins, the surface of which remained close to sea level until at least late Triassic times. If this suggestion of thermal support is correct, then it follows that the delayed subsidence between about 240 and 190 Ma may also be due to the residual support of a mantle thermal anomaly.

An alternative viewpoint is that the basement surface of the future WSB was well above sea level during the Permian (for reasons unknown), and that the extension event at the end of the Permian and in the early Triassic was relatively minor. This does not, however, account for the rapid Triassic subsidence in the SG-6 borehole sequence. It would also necessitate substantial post-180 Ma rifting, extension and subsidence which are not evident in the seismic profiles and the subsidence data.

6. Magmatism in the West Siberian Basin

Basaltic rocks have been recovered from many boreholes in the WSB (e.g., Aplonov, 1995; Reichow et al., 2005) (see Figs. 1 and 2). We have obtained 63 samples from 12 boreholes distributed widely across the central part of the basin. Our geochemical and radiometric age data (Reichow et al., 2002; 2005) confirm suggestions by Russian workers (e.g., Al'Mukhamedov et al., 1999; Medvedev et al., 2003) that many of these basalts are contemporaneous with, and probably part of, the main Siberian Traps found on the Siberian Craton. A thick sequence of basalts in the basin was drilled in the SG-6 superdeep well. Over 1 km of basalt was penetrated, and seismic data indicate that a further 1–2 km of basalts underlie this (e.g., Westphal et al., 1998). At least some of the basalts are effusive; logging data from boreholes indicate the presence of brecciated flow tops and vesicular (amygdaloidal) flow interiors. The occurrence of gabbroic rocks in some boreholes suggests that some units may be intrusive. Basaltic rocks of Triassic age have also been reported from the Kuzbass Basin (Kruk et al., 1999) to the southeast of the WSB, but their eruptive age requires confirmation.

Unfortunately, and as mentioned earlier, it is not possible to distinguish basaltic units on the seismic sections we studied, so we were unable to determine either the precise extent of the basalt subcrop or, in most instances, whether basalts were cut by faults or postdate the faults and pond within rift valleys.

Details of the geochemistry of the WSB basalts are given in Reichow et al. (2005), and we summarise their findings here. Despite the high degree of alteration, the many of the analysed basalts are comparable with tholeiites of the Nadezhdinsky suite found in the Noril'sk succession. None of the basalts analysed by Reichow et al. (2005) resemble mid-ocean ridge basalts. This finding is counter to that of Aplonov (1988) who proposed the existence of an aborted Permo-Triassic ocean basin (the Obsky Ocean) in the basement of the WSB.

The composition and petrogenesis of the Siberian Traps from Noril'sk are detailed in several papers (Lightfoot et al., 1990; Wooden et al., 1992,1993; Sharma et al., 1991,1992; Naldrett et al., 1992; Hawkesworth et al., 1995; Fedorenko et al., 1996; Sharma, 1997), and it is not necessary to repeat those details here. Fig. 7 is a plot of La/Sm versus Gd/Yb, a convenient method of demonstrating variations in both light rare earth elements (REE) (La/Sm) and heavy REE (Gd/Yb) on the same diagram. We have included sets of oceanic basalts, which provide a useful indicator of depth of melting uncomplicated by the effects of crustal contamination. N-type mid-ocean ridge basalts (N-MORB) have the lowest La/Sm and Gd/Yb values of terrestrial basalts, consistent with derivation from a light-REE depleted source that has undergone a shallow average depth of melting. Under these conditions, the effect of residual garnet is small.

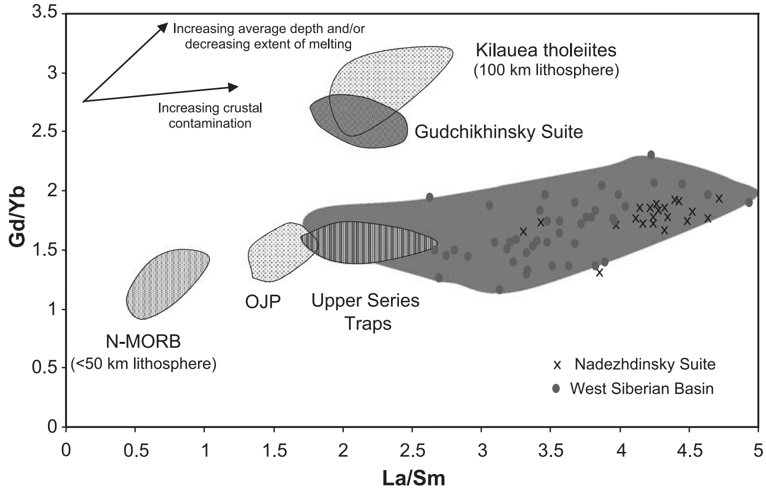

Fig. 7. La/Sm versus Gd/Yb for tholeiitic basalts from the West Siberian Basin and Noril'sk (Gudchikhinsky and Nadezhdinsky Suites, and the Upper Series), and from various oceanic settings. Note the wide range of compositions exhibited by the WSB basalts, many overlapping with the Nadzhedinsky Suite from Noril'sk. Data sources—Kilauea: Chen et al. (1996); MORB: ADS, unpublished data; Ontong Java Plateau: Babbs (1997) and Fitton and Godard (2004); Siberian Traps: Gudchikhinsky suite, Lightfoot et al. (1990) and Wooden et al. (1993), Nadezhdinsky Suite and Upper Series basalts (Morongovsky, Mokulaevsky, Kharaelakhsky, Kumginsky and Samoedsky suites), Lightfoot et al. (1990) and Hawkesworth et al. (1995); West Siberian Basin: Reichow et al. (2005).

In contrast, tholeiites from Hawaii have significantly higher Gd/Yb, consistent with a substantially greater average depth of melting (>100 km), and consistent with their formation below a thick lithospheric lid in the presence of residual garnet (e.g., Watson and McKenzie, 1991). Tholeiites from the Ontong Java Plateau have slightly higher La/Sm than N-MORB, reflecting derivation from a slightly less depleted source. Their slightly higher Gd/Yb indicates a greater average depth of melting than MORB, but less than Hawaii (Neal et al., 1997; Fitton and Godard, 2004).

Data for basalts from the WSB and the Siberian Traps are included in Fig. 7. The three lower suites from Noril'sk (the Ivakinsky, Syverminsky and Gudchikhinsky suites) have La/Sm and Gd/Yb similar to Hawaiian tholeiites, consistent with the interpretation of Sharma et al. (1992) and Wooden et al. (1993) that these were derived from a deep sub-lithospheric source (from beneath a lithosphere of at least 100 km), with small amounts of crustal contamination. Such deep melting implies a mantle source with elevated potential temperatures, in order to produce the observed composition and volume of basalt. The majority of Siberian Traps and WSB basalts, including the Nadezhdinsky Suite and the basalts of the voluminous Upper Series from Noril'sk, however, have Gd/Yb similar to basalts from the Ontong Java Plateau, but with higher La/Sm. The low Gd/Yb values indicate shallow and/or extensive melting of the mantle source regions. The high La/Sm (and La/Nb and Ba/Nb: Reichow et al., 2005) in the Nadezhdinsky suite and many of the WSB basalts indicates that they contain a substantial lithospheric component. Unfortunately, we do not have isotope data to constrain the origin of this lithospheric component, but crustal assimilation (Arndt and Christensen, 1992; Arndt et al., 1993; Reichow et al., 2005) is likely. Some of the WSB basalts have low La/Sm ratios (<3), similar to basalts from the Upper Series traps of the Noril'sk area (Fig. 7).

7. General discussion

The main aim of this study is to investigate the role (or otherwise) of a mantle plume in the formation of the Siberian Traps. Numerical models (e.g., Griffiths and Campbell, 1991; Farnetani and Richards, 1994) predict, and observation (e.g., Courtney and White, 1986; Jones and White, 2003; He et al., 2003) supports the idea that a plume should generate substantial amounts of uplift of the overlying lithosphere. The precise amount of uplift observed at the Earth's surface is difficult to quantify, because of the large number of variables (thickness and rheology of the lithosphere; buoyancy—both thermal and compositional—of the plume; viscosity of the plume and the surrounding mantle), many of which are imprecisely known. Most models predict at least 500 m uplift—some models predict considerably more—during the development of a start-up plume, over a wide region (several hundred kilometers), and with maximum uplift occurring a few million years before peak rates of basalt magma production.

It was this prediction of regional uplift that has led some workers to reject the notion of a mantle plume origin for the Siberian Traps because, not only is there scant evidence of uplift in the area of Noril'sk, but there is also a suggestion that the Noril'sk area was undergoing *subsidence* at the time of basalt emplacement (e.g., Czamanske et al., 1998; Tanton and Hager, 2000). The evidence against Permian uplift is based on the sedimentary and palaeontological facies preserved in the pre-and syn-basalt sequences on the Siberian Craton. These indicate that the environment stayed close to sea level (predominantly lagoonal) before and throughout much of the eruptive period (e.g., Fedorenko, 1991; Fedorenko et al., 1996).

The surface elevation of the Noril'sk area may not, however, be a clear indication of the Permian and Triassic mantle dynamics beneath Siberia. Noril'sk sits on the edge of the Siberian Craton, which has a present-day lithospheric thickness well in excess of 300 km and possibly as much as 350 km (e.g., Zhang and Tanimoto, 1993; Artemieva and Mooney, 2001). It is reasonable to assume that this predominantly Archaean structure had a similar thickness during the Permian. Given that the majority of the basalts from Noril'sk and the WSB were derived by melting at substantially shallower depths than this, we can effectively rule out the region beneath the craton as the primary source for the magmas. This indicates large-scale lateral movement of magma, either through the crust or at the surface (e.g., White and McKenzie, 1989), and across the craton.

Czamanske et al. (1998) proposed that the Siberian Traps formed at the boundary between the thick lithosphere of the Siberian Craton and the substantially thinner lithosphere of the WSB. Utilising the 'edge' model developed by King and Anderson (1995, 1998), they argued that a body of warm mantle formed beneath the Siberian Craton as a result of the thermal insulation by the craton, which trapped heat migrating from the deeper mantle. This warm asthenospheric mantle then flowed laterally from beneath the craton, and upwards into the region beneath the thin lithosphere of the WSB. Melting occurred where the warm mantle underwent active decompression, i.e., at the edge of the craton and, arguably, where the basalt sequences are thickest (e.g., at Noril'sk). The model also predicts that secondary circulation cells would develop, leading to even greater magma production, at the craton margin (King and Anderson, 1998). We shall return to the edge model below, but at this point we simply note that the emplacement of hot, buoyant mantle beneath thin lithosphere should cause some regional uplift, whether it was emplaced by a plume or via the edge model.

Was the main source of the Siberian Traps magmatism located beneath the West Siberian Basin? The scant record of mid-and late-Permian geology beneath the WSB indicates that much of the region was emergent. This elevation has traditionally been linked to a Hercynian tectonic event (e.g., Peterson and Clarke, 1991), but we argue instead that the uplift may be a result of sub-lithospheric thermal buoyancy. There is clear evidence of faulting and rifting throughout the WSB, with β factors of about 1.1 in the central part of the basin, and up to 1.6 in the northern part, and yet the northernmost basin remains predominantly continental throughout the Triassic.

The subsidence curves from Urengoy-414 and SG-6 boreholes show that there was delayed thermal subsidence in this region throughout the Triassic, but further work is needed to confirm whether this was caused by residual thermal support or some other mechanism. From the early Jurassic, the WSB appears to have undergone steady thermal subsidence up until the Neogene. The thermal anomaly responsible for the Permo-Triassic uplift and magmatism had, by this time, disappeared, perhaps as the Siberian plate moved away from the underlying thermal anomaly. Late Triassic and Jurassic basalts, dolerites (E. Eide, personal communication) and anorogenic granites (Vernikovsky et al., 2003) found in the Taimyr Peninsula suggest that the locus of magmatic activity was moving towards the Kara Sea. The High Arctic large igneous province (Maher, 2001) as recorded on the Barents Shelf and exposed on Franz Josef Land, Kong Karls Land, Svalbard, the Alpha Ridge and Ellesmere Island, may be the Mesozoic expression of the same thermal anomaly that gave rise to the Siberian Traps, and there is even the intriguing speculation that it currently resides beneath Iceland (e.g., Bailey and Rasmussen, 1997; Lawver et al., 2002).

Any model to explain the Siberian Permo-Triassic magmatism has to take into account the following factors. (i) Their widespread distribution across both the WSB, the Siberian Craton and the Maymecha-Kotuy region: an original eruptive area perhaps as large as 4.5×10^6 km^2. (ii) A predominance of tholeiitic basalts throughout the main eruptive sequences, with trace element compositions that strongly indicate shallow depths of melt generation (<100 km). These basalts occur atop both thick craton and much thinner, rifted lithosphere: composition cannot be directly related to their location. (iii) Formation of early suites in the Noril'sk succession (e.g., the Gudchikhinsky Suite) at melting depths equivalent to present-day Hawaii, indicating high source temperatures. (iv) The rapid 'switching on' of the magmatic province. Activity at 251 Ma appears ubiquitous, and is recorded in areas as far apart as the WSB (Reichow et al., 2002), Noril'sk (Renne and Basu, 1991; Campbell et al., 1992; Kamo et al., 1996; Venkatesan et al., 1997), and Maymecha-Kotuy (Kamo et al., 2003). Younger activity may have persisted farther north (e.g., Westphal et al., 1998), but this needs to be confirmed by radiometric dating. (v) The short duration of the igneous activity (e.g., Renne and Basu, 1991; Lind et al., 1994; Kamo et al., 2003). Estimates vary, but range from 0.6 Ma for the activity at Noril'sk, to approximately 2 Ma for the province as a whole. Given that large areas of the province, especially in the northern WSB, have not been sampled or dated, this should be treated with caution, but the age of activity at Noril'sk appears well constrained. (vi) Lack of uplift over much of the Siberian Craton, but the evidence of uplift and thermal support in the WSB. (vi) Closely contemporaneous rifting and magmatism in the WSB.

There appears to be a requirement for some form of thermal anomaly in the mantle beneath this region of Siberia during Permo-Triassic times. Melting of hydrated lithospheric mantle could account for the high La/Sm and Ba/Nb of the basalts in the WSB, and this is a model that has been advocated for some other continental flood basalts (e.g., Tasmanian dolerites, and Paraná: Hergt et al., 1991; Hawkesworth et al., 2000). However, melting of lithosphere still requires an external energy source (Hawkesworth et al., 2000). In the case of the Paraná province, a sublithospheric source of energy, the Tristan plume, is proposed.

The question then reduces to what the mechanism was that formed the thermal anomaly beneath Siberia: a mantle plume; some form of 'edge' effect; or a bolide impact. The suggestion that large igneous provinces may be produced by impact of large bolides has received renewed attention (e.g., Jones et al., 2002; Ingle and Coffin, 2004). We note, however, that no known Phanerozoic large impact craters (e.g., Chicxulub or Manicouagan) are associated with basaltic eruptions, and no craters have been found associated with large igneous provinces (although they could be buried beneath the lava pile). Recently, Ivanov and Melosh (2003) have argued that a realistically sized impactor is unlikely to transfer sufficient energy to, or cause sufficient decompression of, the mantle to trigger basaltic magmatism. Given the current evidence, we therefore do not consider this mechanism as a likely explanation for the Siberian Traps; an internal, rather than external, mechanism is preferred.

The 'edge' model (King and Anderson, 1995, 1998) cannot easily account for the widespread magmatism across the WSB, nor can it account for the short duration of magmatism in this and several other large igneous provinces. It has no obvious on/off mechanism, and we would expect the magmatism to continue for several millions of years at the craton margin. The Siberian magmatism is very widespread, not least across the WSB, and is not obviously restricted to the edge of the craton. Both the 'edge' model and the plume models should produce uplift of thin lithosphere adjacent to the craton, so the presence or absence of uplift cannot be used to distinguish between these models. Given the requirements outlined above of any model, we prefer the plume model to best account for the Siberian Traps, as advocated by several other authors (e.g.,Morgan, 1971; White and McKenzie, 1989; Campbell and Griffiths, 1990; Renne and Basu, 1991; Wooden et al., 1993; Lightfoot et al., 1993; Reichow et al., 2005).

8. Conclusions

The sequence of events that we envisage for the region is as follows:

(i) Uplift, or thermal support, of the northern part of the nascent WSB began during the Permian (the precise timing is uncertain). Rifting, due to E–W extension, may have accompanied the uplift, but we are unable to determine when rifting began. We propose that the uplift was generated by accumulation of sublithospheric mantle, with a substantially elevated potential temperature, beneath the thin lithosphere of the WSB, perhaps by the arriving head of a start-up plume (Griffiths and Campbell, 1991). Little (if any) uplift of the Siberian Craton is predicted in this scenario, hence explaining the lack of uplift found in the Noril'sk region and other parts of the craton (Czamanske et al., 1998).

(ii) Late Permian–Triassic rifting, possibly caused by the doming effect of the regional uplift, resulted in the formation of the major rift structures in the WSB, and may have contributed to the release of the Siberian magmas. However, it is difficult to see how extension alone could have generated the large volumes of magma, as the time scales of the two processes differ by an order of magnitude. The arrival of a start-up plume head (Campbell and Griffiths, 1990), or some other massive increase in the mantle flux rate, appears to be necessary. That the sedimentation in the WSB remained continental, or close to sea level, throughout much of the early Triassic, despite the degree of extension, is also consistent with some form of thermal support of the nascent basin floor.

(iii) Initially, high pressure melting (roughly equivalent to the depth of melting beneath modern-day Hawaii) of the hot plume mantle produced the moderate pressure magmas of the early Ivakinsky, Syverminsky and Gudchikhinsky suites of the Noril'sk area. It may be an artefact of sampling that these basalt types have not been recovered from the main area of the WSB. Alternatively, it may be because they were restricted to the northern part of the basin or that, because they are the earlier magmas to be erupted, they are simply at the bottom of the lava piles and have not been drilled.

(iv) Basalts of the Noril'sk Nadezhdinsky suite, and many of those from the WSB, show strong evidence of crustal contamination of shallow mantle derived magmas. Some WSB basalts have low La/Sm ratios, consistent with less crustal contamination, and more closely resemble basalts from the upper sequence traps of the Noril'sk area.

(v) The voluminous Upper Series traps of the Noril'sk succession represent the dominant magma type of the Siberian continental flood basalts, and comprise the bulk of the sequences now found on the Siberian Craton in Putorana and Tunguska. These appear to represent the main episode of melting of the mantle plume, albeit with some lithospheric contamination.

(vi) We suggest that the main site of magma generation was located primarily in the northern WSB (effectively in the Khudosey and Urengoy rifts), and that the magmas travelled onto the craton either across the land surface, and/or through the crust as dykes or sills. Studies of flow directions in lavas from Noril'sk are consistent with this suggestion (Callot et al., 2004).

(vii) Following the main period of continental flood basalt formation, the locus of magmatism migrated northwards to what is now the Taimyr Peninsula, and thence onto the Barents Shelf. The West Siberian Basin then underwent thermal subsidence (initially delayed).

More work is needed on the deep geology of the northern WSB, not least high quality seismic and radiometric age data to resolve the full distribution, thickness and age of the basaltic sequences. It is also necessary to track the plume that was responsible for the magmatic and tectonic activity of the Siberian Traps, if it continued to exist after 250 Ma.

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