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SPECIAL

Oblique rift geometry of the West Siberian Basin: tectonic setting for the Siberian flood basalts

MARK B. ALLEN[1], LESTER ANDERSON[2], ROGER C. SEARLE[1] & MISHA BUSLOV[3]

[1]*Department of Earth Sciences, Durham University, Durham DH1 3LE, UK (e-mail: m.b.allen@durham.ac.uk)*

[2]*CASP, Department of Earth Sciences, University of Cambridge, West Building, 181A Huntingdon Road, Cambridge CB3 0DH, UK*

[3]*United Institute of Geology, Geophysics and Mineralogy, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia*

We use magnetic intensity data to determine the geometries of basalt-filled rifts of the West Siberian Basin. En echelon graben arrays suggest a component of right-lateral, north–south shear during east–west extension (present co-ordinates). Several major exposed faults at the basin margins, mainly within the Altaid orogenic belt, underwent right-lateral strike-slip in the Late Permian–Early Triassic interval. The combined datasets show that the Siberian flood basalts were erupted during right-lateral oblique extension between the Urals and the Siberian craton, centred on a triple junction in the NE of the West Siberian Basin.

The Siberian flood basalts form the largest known continental flood basalt province on Earth. Eruption occurred at the end of the Permian–early Triassic, coinciding with and a possible cause of the Permo-Triassic extinction event (Renne *et al.* 1995). Basalts were erupted across a vast area of the Siberian craton and West Siberian Basin, over an original areal extent of *c.* 5×10^6 km^2 (Vyssotski *et al.* 2006). Melt generation is thought to be the result of a hot mantle plume (Basu *et al.* 1995). Radiometric ages suggest a very short duration of eruption, of the order of 1 Ma (Renne & Basu 1991; Reichow *et al.* 2002), although the magnetostratigraphy of lavas in deep borehole SG6 (66°N, 78.5°E) suggests a duration of several million years (Westphal *et al.* 1998).

Basaltic magmatism was coincident with, and possibly promoted by, rifting in the West Siberian Basin, which continued to a poorly constrained time in the Triassic (Saunders *et al.* 2005). The West Siberian Basin covers *c.* 2.5×10^6 km^2, located over basement created or assembled in the Altaid orogeny (Şengör & Natal'in 1996). It lies east of the Urals orogenic belt (e.g. Brown & Juhlin 2006) and west of the Siberian (Angaran) craton (Vyssotski *et al.* 2006; Fig. 1). Thicknesses of the synrift clastic deposits and interbedded volcanic rocks vary, but reach >3 km (Peterson & Clarke 1991). The flood basalts within the basin are partly within grabens generated by the rifting, but are also present across intervening basement highs, especially in the north (Fig. 1; Surkov 2002).

Total sediment thickness in the north of the basin reaches as much as 15 km (Pavlenkova *et al.* 2002). Even the deepest wells in the basin, such as SG6 (>7 km) do not constrain the stratigraphy of the lower part of this succession, such that extension estimates based on well backstripping underestimate the maximum extension. The stratigraphy of SG6 has been used to estimate an extension factor (β) of *c.* 1.6 (Saunders *et al.* 2005). In 2004, 7% of the world's oil production was from the basin (Vyssotski *et al.* 2006), almost entirely from Jurassic and Cretaceous clastic rocks deposited during the post-rift thermal subsidence phase of the basin.

Thus the rifting of the West Siberian Basin is relevant for a major example of the following: an intracontinental basin, a flood basalt event, a mass extinction and world-class hydrocarbon province. We present a new interpretation of the rift kinematics of the West Siberian Basin and adjacent areas in the Late Permian–Early Triassic interval, based on the pattern of magnetic anomalies, existing fault maps and recent geochronological data. Our model invokes right-lateral shear between the East European and Siberian cratons, instead of simple orthogonal east–west extension as previously inferred for the greater part of the basin.

Magnetic anomalies. Magnetic anomaly data are derived from two merged sources: National Geophysical Data Center (1996) and Verhoef *et al.* (1996) (Fig. 2). The former dataset covers the onshore former USSR, based on 1:2.5 million scale residual magnetic intensity maps published in 1974 by the Ministry of Geology of the USSR. The latter dataset covers offshore Arctic regions. Resolution is about 3 arc minute or 2.5 km. Anomalies are present in the West Siberian Basin despite the thick cover of Jurassic to Tertiary strata, because of the high magnetic signal of basaltic successions in the rifts (Schissel & Smail 2001) and contrasts in the level and nature of the basement exposed in hanging walls and footwalls of the rift blocks. In addition to shaded relief anomalies, we used a variety of band-pass and directional filters in both the spatial and frequency domains (Wessel & Smith 1998) to help identify magnetic lineations (Fig. 2).

The magnetic data clearly show the main north–south Koltogor–Urengoy and Khudosey grabens (Fig. 1), in agreement with published maps of their location and gross structure (e.g. Surkov 2002; Saunders *et al.* 2005). There are individual magnetic highs and lows within the overall trend of these features, which may correspond to individual fault blocks. The main north–south features change trend in their southern sectors, where they have a more NNE–SSW or NE–SW orientation across the central part of the basin. There are more fault blocks at latitude *c.* 60°N than further north, consistent with observations of the rift structure derived from seismic data (Saunders *et al.* 2005). These central anomalies also link into a pronounced set of anomalies that lie along the western side of the basin, apparently splaying off the eastern side of the Urals. These western structures are consistent with the locations of Triassic volcanic rocks and clastic sediments identified in this region (e.g. Surkov & Zhero 1981).

Between 50 and 60°N, the anomalies in the basin interior appear to overprint another set of anomalies that trend roughly NW–SE or are convex northwards (Fig. 2). Members of the earlier set continue to the SE into the exposed Palaeozoic fault systems of the Altaids, and so are likely to represent Altaid faults

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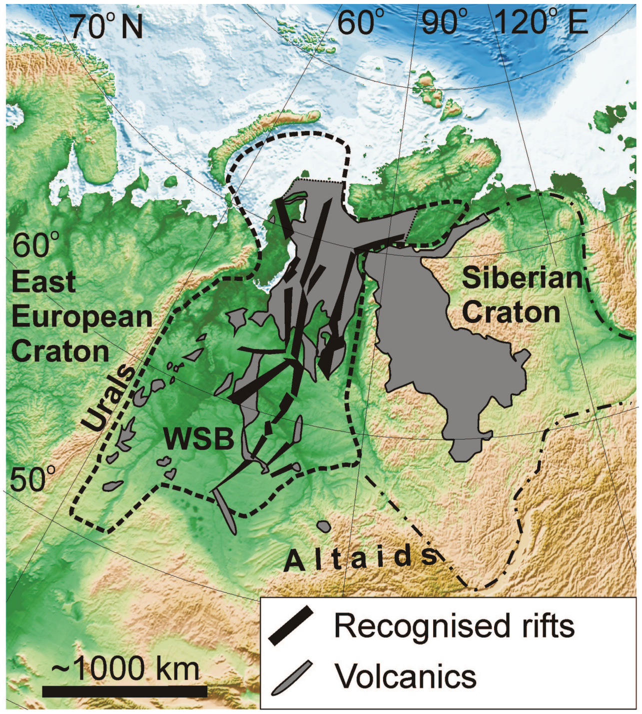

Fig. 1. Tectonic map of the West Siberian Basin (WSB), Siberian Craton and adjacent regions. Distribution of West Siberian rifts and basalts from Surkov (2002).

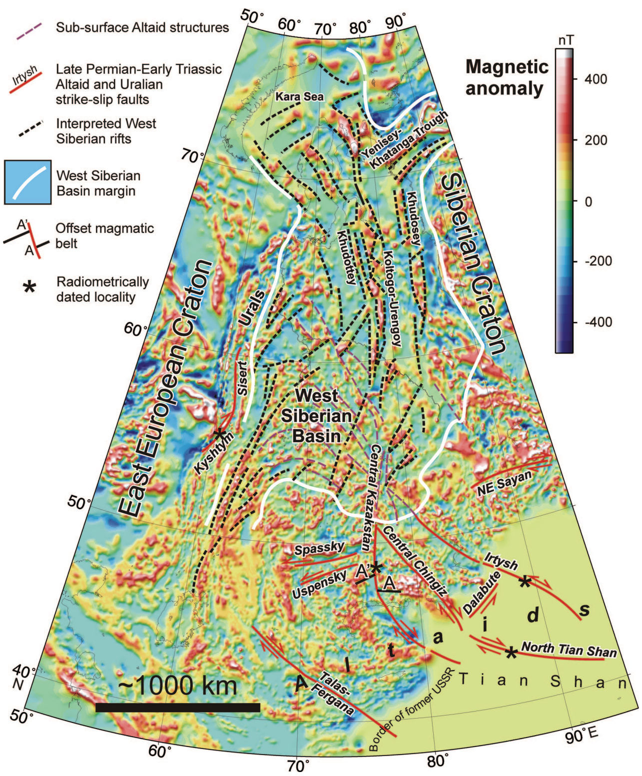

Fig. 2. Magnetic anomaly map of the West Siberian Basin and adjacent regions, showing linear anomalies interpreted as rift zones and exposed faults with Late Permian–Early Triassic strike-slip motion. Anomalies are colour-coded, and illuminated from the NW.

in the basement of the West Siberian Basin (Şengör & Natal'in 1996). It is not clear that the Altaid faults are offset laterally by the later structures: possible offsets are ambiguous.

At the northern side of the basin and in neighbouring offshore areas there are different patterns in the magnetic anomalies. ENE–WSW trends in the Yenisey–Khatanga Trough are parallel to the margins of this continuation of the West Siberian Basin. NW–SE-trending anomalies pass across the Yamal Peninsula into the Kara Sea. Combined with the north–south trends further south in the basin, these magnetic anomaly patterns define a triple junction (Aplonov 1995; Schissel & Smail 2001), but we do not find convincing evidence of oceanic crustal stripes in the anomaly patterns, as suggested by Aplonov (1995).

Strike-slip fault kinematics. The kinematics of faults exposed at the margins of the West Siberian Basin helps reconstruct the deformation history of the basin itself, by showing the relative motion of crustal blocks at key time intervals. This section summarizes the structures with direct or indirect evidence for Late Permian–Early Triassic motion (Fig. 2), to help interpret the evolution of the West Siberian Basin over this time. Strike-slip forms an important, if not dominant, aspect of the kinematics. Faults for which Late Permian–Early Triassic strike-slip has been dated radiometrically using fault rock minerals include the Kyshtym Shear Zone, Irtysh Shear Zone, Central Kazakstan Fault and faults in the Chinese Tian Shan.

The Kyshtym Shear Zone in the Middle Urals was active under retrograde lower amphibolite- to middle or lower greenschist-facies conditions (Hetzel & Glodny 2002). Four metagranitic, muscovite-bearing mylonites give Rb–Sr internal mineral isochron ages of 247.5 ± 2.9, 244.5 ± 6.5, 240.0 ± 1.4 and 240.4 ± 2.3 Ma (i.e. Early Triassic), interpreted as indicating the time of shear on the fault zone. Total right-lateral offset is estimated as 43 ± 15 km. The Sisert Fault is undated, but may represent a northern continuation to the Kyshtym Shear Zone. Other range-parallel strike-slip faults are present in the Urals, but they are either earlier than Late Permian or not well-dated, and both left- and right-lateral offsets are recorded (Brown & Juhlin 2006).

Within the Altaids, the Chinese segment of the Irtysh Shear Zone underwent late stage slip at *c*. 245 Ma, apparently with subparallel, synchronous, right-lateral and left-lateral shear zones (Laurent-Charvet *et al*. 2003), following earlier polyphase slip along the same fault system. The Central Kazakstan Fault trends north–south, clearly offsetting older faults and volcanic belts that trend NW–SE. It truncates granites mapped as Late Permian by Zonenshain *et al*. (1988), which are part of the granitoid zone given K–Ar ages of 280–230 Ma by Kostitsyn (1996). A dyke swarm that is not affected by the shearing has a K–Ar age of 252 ± 8 Ma (Kurchavov 1983), constraining the slip as no later than Late Permian or Early Triassic. A late Palaeozoic volcanic zone appears to be offset in a right-lateral sense by *c*. 60 km (Zonenshain *et al*. 1988); a distinct magnetic high in the same region (Fig. 2) is offset by a similar amount. Within the Chinese Tian Shan, $^{40}Ar/^{39}Ar$ ages for syntectonic biotites indicate right-lateral shearing at 250–245 Ma, i.e. near the Permo-Triassic boundary (Laurent-Charvet *et al*. 2003). This overprints earlier right-lateral shear dated as far back as 290 Ma.

Other faults south of the West Siberian Basin have not been dated radiometrically, but Late Permian and/or Early Triassic slip is indicated by the ages of offset features and/or sedimentation in associated basins. This group includes the Central Chingiz, Spassky, Uspensky, Northeast Sayan, Talas–Fergana and Dalabute faults (Fig. 2) as described below.

Within the Altaids, Zonenshain *et al*. (1990) described several faults as being active at the end of the Permian. The Central Chingiz Fault trends NW–SE through eastern Kazakstan into NW China, where it merges into the thrusts and strike-slip faults at the northern side of the Tian Shan. Both of the Spassky and Uspensky faults are east–west structures at the west of the Central Kazakstan Fault. They were described as left-lateral, Late Permian features by Zonenshain *et al*. (1990), but without more detail. They appear to cut through the east–west-trending Spassky Thrust Belt, which was active in the Carboniferous. The Northeast Sayan Fault is a right-lateral fault that displaces NW–SE-trending structures that were active between the late Devonian and early Permian, and is itself intruded by Triassic–Jurassic granitoids. The fault is thus inferred to have been active in the Permo-Triassic (Buslov *et al*. 2003). Offset is of the order of 20 km.

Within the Tian Shan, Permian right-lateral motion on the Talas–Fergana Fault was a late feature of collision of the Tarim Block with the southern side of the Altaid collage. This right-lateral deformation began in the Late Permian, and continued into the Triassic (Burtman 1980). Pre-Cretaceous right-lateral slip was 130–200 km. To the north of the Tian Shan, the linear Dalabute Fault contains late Permian continental clastic deposits and acidic volcanic rocks in pull-apart basins along the fault zone (Allen & Vincent 1997). The sense of slip along the Dalabute Fault in the Late Permian is uncertain, but neighbouring faults with the same NE–SW orientation are left-lateral.

Discussion. The rifts imaged by magnetic anomaly data and the histories of major strike-slip faults at the basin margins permit a new model for the kinematics of the West Siberian Basin (Fig. 3). East–west extension across the West Siberian Basin is indicated by the north–south orientation of major grabens, but the grabens with a NE–SW orientation imply a more complex kinematic story, involving a component of NW–SE extension (Figs 2 and 3). Their left-stepping, en echelon distribution indicates a component of right-lateral, north–south shear during extension. Fault block rotations about vertical axes are likely in these circumstances, but are not independently confirmed. Linear, positive magnetic anomalies in the SW of the basin trend roughly NE–SW or NNE–SSW, and have a left-stepping, en echelon pattern. These features are consistent with being basalt-bearing grabens, as shown in some but not all structural compilations for this area, and interpreted by Şengör & Natal'in (1996) as the result of local right-lateral oblique extension. Similar arrays of anomalies in the SE of the basin have the correct orientation to be trailing extensional splays to the right-lateral Central Kazakstan Fault. Recent geochronological data for exposed faults show that major right-lateral strike-slip occurred to the south of the basin in the Late Permian–Early Triassic. Firm data exist for strike-slip to the west, in the Urals (Hetzel & Glodny 2002), but are far more limited. Individual faults have differing orientations, but several are north–south or NW–SE. Shorter, rarer faults were left-lateral at this time, typically with ENE–WSW or NE–SW orientations. Possibly, these were antithetic to the main right-lateral structures.

Collectively, these data suggest that West Siberian rifting occurred during regional right-lateral oblique extension in the Late Permian–Early Triassic (Fig. 3), rather than simple, orthogonal east–west extension as conventionally inferred from the north–south orientation of major rifts such as Koltogor–Urengoy. Such right-lateral motion is consistent with the right-lateral shear invoked elsewhere in Eurasia at this time to explain the basement structure of the Turan and Scythian platforms (Natal'in & Şengör 2005).

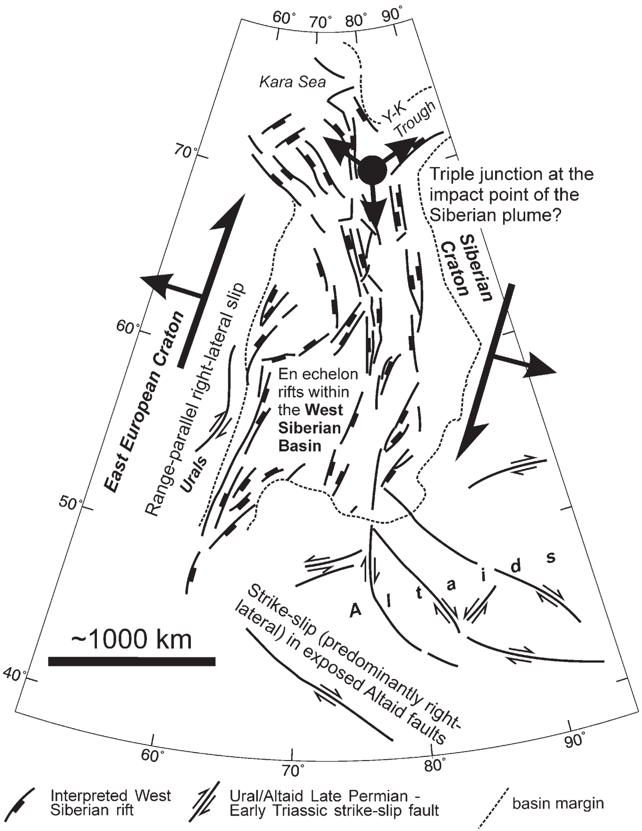

Fig. 3. Model for the rift kinematics of the West Siberian Basin. This invokes right-lateral shear between the East European and Siberian cratons, and a triple junction in the northeast of the basin. Normal fault segments defined from magnetic anomaly data (Fig. 2), with polarity information from Nikishin *et al*. (2002) and Saunders *et al*. (2005). Y-K, Yenisey–Khatanga.

Some strain partitioning occurred during the West Siberian rifting, with part of the right-lateral motion taking place on major strike-slip fault zones, away from or at the margins of the basin (e.g. along the Central Kazakstan Fault). The displacement of each individual fault at the West Siberian Basin margins is typically several tens of kilometres, where known accurately. This is relatively small compared with the >1000 km width of the basin, but does not take into account possible right-lateral motion within the basin interior, by either pure strike-slip displacement or rotation of fault blocks about vertical axes. The overall fault geometry of the West Siberian Basin resembles other large continental rift basins interpreted to have formed by oblique extension (e.g. Beauchamp 1988), particularly in the combination of marginal strike-slip faults and en echelon rifts within the basin interior.

The fault geometries in the northern part of the West Siberian Basin do not fit this simple oblique-extension model, but this may be the result of the mantle plume inferred from the volume and geochemistry of the Siberian flood basalts, and the subsidence history of the basin. The triple junction of rifts in the north of the basin (Aplonov 1995) may indicate a mantle plume impact in this region (Schissel & Smail 2001). Consistent with this idea, the greatest post-rift subsidence and sedimentation has taken place in this part of the basin (Peterson & Clarke 1991), and the area was the focus of basaltic magmatism within the basin (Surkov 2002). It is also adjacent to the thickest exposed successions of the Siberian Traps, in the Noril'sk region (Sharma 1997).

These data suggest that the greatest crustal stretching and thinning and the greatest melt generation all occurred in the area of this putative triple junction, consistent with the mantle plume hypothesis, and suggesting that a plume impact was a major control on the rift structure of the West Siberian Basin. Triple junction geometries are typical of other flood basalt provinces such as the Deccan and Afar. However, there is no *a priori* reason why a plume should cause oblique extension, and we propose that the right-lateral component to the rifting was related to motion between the East European and Siberian cratons, independent of plume activity. Given that the present north–south rifts were closer to an east–west orientation in the Late Permian (Torsvik & Cocks 2004) this oblique extension model may be difficult to detect palaeomagnetically, but it will be testable as further data emerge on the fault kinematics of central Asia, and is consistent with existing data (Natal'in & Şengör 2005). Our model is clearly preliminary, and much more needs to be done on the timing, kinematics and underlying causes of extension in this vast and enigmatic basin.

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