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Positioning Paleogene Eurasia problem: Solution for 60–50 Ma and broader tectonic implications

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Abstract

Recently published paleomagnetic data from the Faroe Islands and SE England have enabled a "hybrid" pole (72.0°N, 177.9°E, A_{95} = 7.9°) to be calculated for "stable" Eurasia ~55 Ma. It is somewhat different to previous proposals, being a further 8–9° from the present-day North Pole. A strong positive test of the new pole is provided by 2002-published paleomagnetic data from basaltic rocks in the Tien Shan range in Kyrgyzstan: the paleolatitude derived from the inclination angle matches the predicted value to within 0.2°. An unfortunate drawback with Kyrgyzstan pole is its large age error: ±15 m.y. for rocks estimated to have formed ~50 Ma. Fortuitously, an alternative test is now available using paleomagnetic data from Paleocene basalts in the Tien Shan range of western China, for which a robust radiometric age-date (59±1 Ma, based on two Ar–Ar results) also exists. Although the locality has experienced a large vertical-axis rotation, the mean declination being 54.5°, the inclination angle appears undisturbed, and the derived paleolatitude matches the value predicted by hybrid pole to within 4.0°. Thus, it is contended, the Faroe–Sheppey pole provides one of the most reliable means of fixing Eurasia's position for the interval 60–50 Ma. It also impacts on various model proposals for the India–Asia collision and subsequent crustal shortening and/or extrusion between southern Tibet and stable Eurasia (north of the Tien Shan).

Keywords: Inclination shallowing; Eurasia; Paleomagnetic; Faroe; Sheppey; Tien Shan

1. Introduction

Although Eurasia is one of Earth's largest and slowest moving plates, deducing its exact position in the Cretaceous and Cenozoic is not straightforward. The problem is a consequence of the limited paleomagnetic data-base for Cretaceous and Cenozoic rocks on "stable" Eurasia. Aside from a handful of data for Upper Cretaceous formations, most results are from European North Atlantic igneous province (ENAIP) rocks in NW Britain and the Faroe Islands (Table 1a; see compilations in [1–3]), which were erupted/emplaced in two short intervals ~61 Ma and ~55 Ma. The drawbacks are clear: the area is located at the western tip of the plate and is miniscule (Fig. 1), and there are effectively no data for the long intervals prior to the Selandian and after the Ypresian. Also, Riisager et al. [4] have questioned the validity of the "old" data-set, practically all of which was published in the 1960s and 1970s, arguing that the laboratory processing and direction selection techniques

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Table 1
Apparent pole data from the various locations at 55 Ma

Table 1a

	No. Poles	Pole Lat	Pole Long	A_{95}
Torsvik et al. ([1], Table 1b)	16	77.4	165.8	2.8
Besse and Courtillot ([3], Table 4)	10	81.2	177.3	~3.1
Schettino and Scotese ([34], Table 7)	NS	80.3	179.2	8.0

Table 1b

Study area	Work	No. Outcrops	No. Sites	Dec	Inc	α95	Site Lat	Site Long	Pole Lat	Pole Long	A_{95}	Pmag co-lat
Faroe Islands	Riisager et al. [4]	4	43	8.0	62.5	4.3	60.8	353.0	71.4	154.7	6.0	46.2
Kyrgyzstan Tien Shan	Bazhenov and Mikolaichuk [5]	2	18	14.6	54.0	3.8	40.7	76.1	76.9	189.6	4.5	55.5
Sheppey	Ali et al. [9]	3	9	1.1	43.2	6.8	51.4	0.9	63.7	178.6	6.8	64.9
China Tien Shan	Huang et al. [20]	1	12	54.5	49.4	7.7	40.23	75.25	45.1	160.3	8.5	59.8
Faroe–Sheppey hybrid	Ali and Aitchison [10]								72.0	177.9	7.9	

Table 1a summarizes the major NAIP based compilations, Table 1b details the newer data-sets for the Faroe Islands [4], Sheppey [9], Kyrgyzstan [5] and western China [20]. The Besse and Courtillot [2,3] pole is the intermediate point between their 60 and 50 Ma poles.

used in many of the studies would now be considered inadequate. This, they considered, might explain the somewhat scattered distribution of the ENAIP poles ([4], Fig. 6). They also intimated that a pole they had generated following a major "modern" study of upper Paleocene basalts from the Faroe Islands (Table 1b) might be the most reliable one for positioning Eurasia in the early Cenozoic.

In the same year, an important paper was published following a paleomagnetic investigation of Paleogene basalt sequences (lower part of the Kokturpak Formation) in the Tien Shan range, Kyrgyzstan [5] (Fig. 1). The key finding was that the volcanic rocks in Central Asia did not show the "inclination shallowing" effect that had affected/blighted numerous studies of Cretaceous and Cenozoic sedimentary rocks in various parts of Asia (e.g., [6–8]). Presumably because the Tien Shan locality is within a young-active tectonic zone, where complex vertical-axis rotations might be expected, Bazhenov and Mikolaichuk [5] did not calculate an apparent pole for their studied sequence as they likely presumed that it would have limited tectonic value. However, as will be shown below, this is not the case and the calculated pole is listed in Table 1b.

In an attempt to geographically broaden the paleomagnetic data-base for stable Paleogene Eurasia, Ali et al. [9] undertook a study of cemented nodule bands in three London Clay Formation sections on the Isle of Sheppey, SE England (Fig. 1). The sequences, which together span the interval ~52.7 to ~51.6 Ma (Chrons C24.1n–C23r–C23.2n, Fig. 2), yielded a direction of Dec = 1.1°, Inc = 43.2°, α95 = 6.8°. Although the inclination angle was anomalously low (43.2°, Table 1b, when ~52.9° might have been more appropriate), Ali et al. [9] proposed that the declination, which indicated a negligible rotation, might be useful for modeling the past position of stable Eurasia. Sheppey is a considerable distance from any of the Cenozoic plate boundary zones, the nearest ones being the NE Atlantic spreading centre to the northwest and the Alpine orogenic belt to the south, and the area should thus be tectonically undisturbed.

Arguing that the apparent poles from the Faroe Island [4] and the Sheppey [9] poles had both positive and negative attributes, Ali and Aitchison [10] constructed a "hybrid" pole for 55 Ma Eurasia (Fig. 3a). First, on the basis that the declination angle associated with the Sheppey result was useful (i.e., was un-rotated relative to stable Eurasia), they constructed a great circle between the Sheppey sample site at 51.4°N, 0.9°E and the associated apparent pole at 63.8°N, 178.6°E (Table 2a). Second, assuming that the Faroe Island lavas were unlikely to have shallowed inclinations (but possibly a slight counter-clockwise rotation as the basalt sequences had accumulated on the flanks of the NE Atlantic spreading centre), the mean value from these rocks (using the standard inclination-to-latitude conversion equation) should provide a reliable paleo-latitude/co-latitude estimate. Using the paleomagnetic co-latitude (46.2°, angle between the site and North Pole in the late

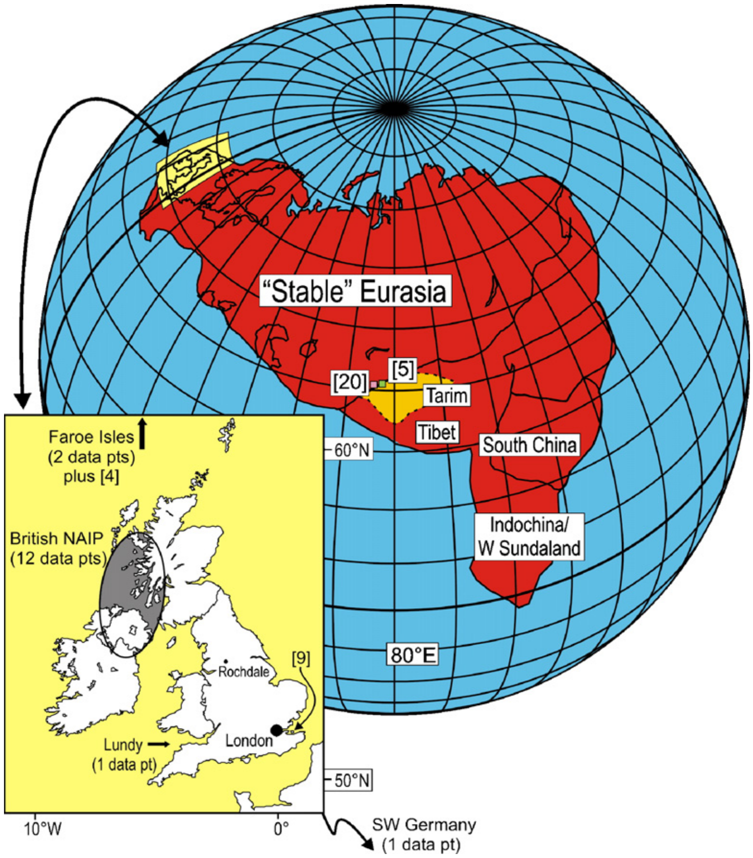

Fig. 1. Orthogonal map projection of present-day "stable" Eurasia together with the "less stable" eastern elements of the continent (drafted using the GMAP software [38]). Areas forming the Alpine–Himalayan belt and India etc. are not shown. The British Isles map illustrates the limited aerial extent from which the stable Eurasia paleomagnetic data-set for the early Cenozoic is based. Also shown is the Sheppey site [9].

Paleocene) to fix the radius, a small circle path was constructed about the Faroe Island site at 61.8°N, 353.0°E (Table 2b). The intersection point of the two circles, 72.0°N, 177.9°E (the A_{95} being set at 7.9°, the value for the Sheppey pole translated to this point), should therefore yield the apparent pole position for early Paleogene Eurasia.

To test the proposal, Ali and Aitchison [10] used Bazhenov and Mikolaichuk's 2002 published data [5] from the Tien Shan range, Kyrgyzstan. They had obtained a useful direction from a series of early Paleogene basalt flows ~40.7°N, 76.2°E. The inclination angle, in particular, provided a useful latitudinal estimate of this part of Central Asia when the lavas were erupted, since the magnetization appeared to be primary.

Now, the Tien Shan is famous for being a young active mountain belt (its highest peak, Pobeda, is 7439 m above sea level), but it is more than 1000 km from the Indian craton which is indenting into Asia and causing the deformation and uplift in the range. The variable orientations and vector lengths of the associated GPS data from the belt [11,12] reveal a complex present-day deformation field. In geologically recent times, shortening has been accommodated principally along approximately E–W oriented folds and thrust faults (north and south dipping) [13–15]. Since tectonic activity in the Tien Shan started in late Oligocene–early Miocene times [16,17,13], we might thus anticipate the Paleogene and older formations outcropping in the orogen to record local vertical-axis rotations. (However, as evidenced from the 2005 updated Global Paleomagnetic Database [18,19] for the Tien Shan, there has not yet been anywhere near enough work in the ~1500-km-long by 200 to 300-km-wide orogen to elucidate the detailed pattern of local and sub-regional vertical-axis rotations.) Thus, although it was not possible to use the apparent pole calculated from Bazhenov and Mikolaichuk's result [5] to position Eurasia directly, the inclination angle could be used to construct a paleomagnetic co-latitude small-circle pole-path (radius of 55.5°). Rotating the pole just 7.0° clockwise (incidentally, the α95 associated with the mean direction was 3.8°)

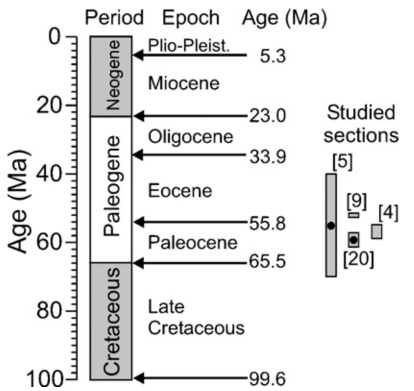

Fig. 2. Age and associated error/age range of the various early Paleogene poles used to construct a hybrid apparent paleomagnetic pole for stable Eurasia. Sections with an age and error [5,20] are shown with black dots and vertical grey bars. The two continuous magnetostratigraphic sequences [4,10] that are tied to the geomagnetic polarity time scale [39] are shown with vertical grey bars.

around the sampling site brought the Central Asia pole to within just 0.2° of the Faroe–Sheppey hybrid pole (Table 2c). This strongly suggested that the hybrid pole proposal [10] carries some weight because the observed paleolatitude (via the standard inclination conversion) for the Kyrgyzstan locality ~55 Ma is effectively identical to that predicted by using the pole.

2. New data from the Tien Shan range, western China

A major drawback with the Kyrgyzstan pole is the uncertainty regarding its age: ±15 m.y. for rocks estimated to have formed ~50 Ma (Fig. 2). Fortunately, however, another data-set has recently been published [20] which provides an alternative test of the hybrid pole. Critically, there is excellent age control on the studied rocks. The new data are from the Chinese Tien Shan, about 95 km WSW of the Kyrgyzstan localities [5]. Directional data were obtained from Paleocene basalt flows and red beds from Tuoyan Basin Outcrop A (40.23°N, 75.25°E), and a parallel Ar–Ar age-dating study indicated that the rocks formed ~59 Ma (actual ages being 58.5±1.3 Ma and 60.4±1.3 Ma) (Fig. 2).

To eliminate any chance of sedimentary-rock inclination shallowing "contaminating" the data, a formation mean direction was calculated using only the basalt-flow site means. Additionally, two volcanic-rock results were eliminated, one because of its large α95 (17.6° for Site ty8), the other due to its anomalous magnetization direction (Site ty10) (for the same reasons, Huang et al. also excluded results from these sites in calculating their locality mean ([20], Table 1). Thus the outcrop averaged direction is based upon 12 sites: ty1–ty7, ty9, ty11–ty13

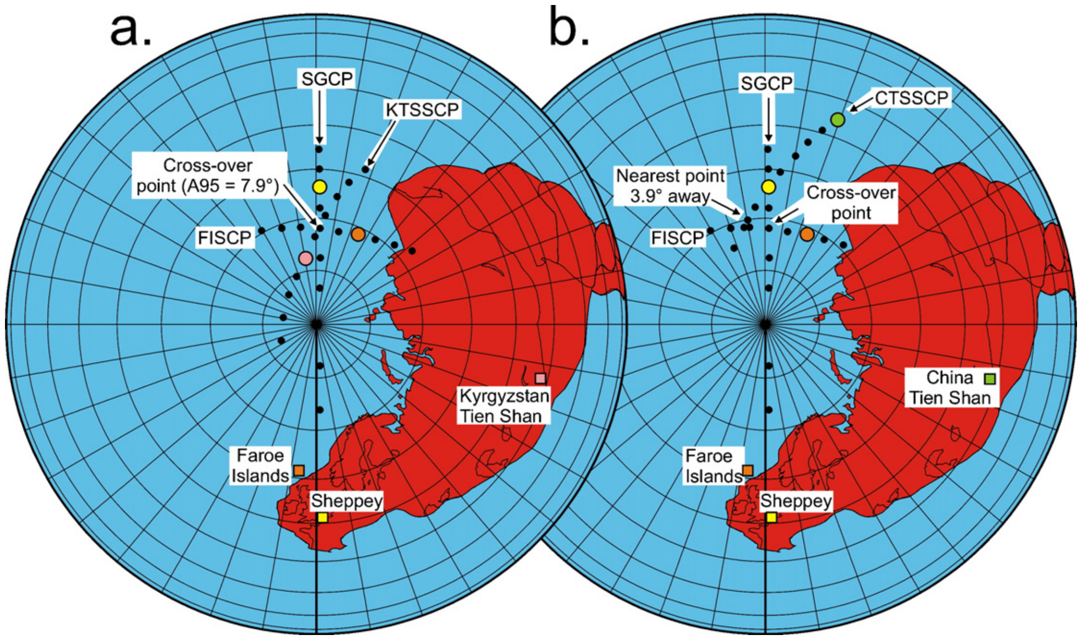

Fig. 3. Positions of the recently published high-quality stable Eurasia apparent poles and related great and small paths (large coloured circles — see Table 1 for the associated statistics). In a, SGCP is the Sheppey great circle path and FISCP/KTSSCP are the small circle paths for the Faroe Island and Kyrgyzstan poles. In b, SGCP is the Sheppey great circle path and FISCP/CTSSCP are the small circle paths for the Faroe Islands and China Tien Shan poles. Sampling locations are shown by the coloured squares.

Table 2
Summary of the Great (Table 2a: Sheppey) and small circle (Tables 2b–d: Faroe Islands, Kyrgyzstan Tien Shan, China Tien Shan) data

Table 2a

Sheppey great circle path points Dec=1.1, Inc=43.2, pmag co-lat=64.9° Site Lat=51.4°, Site Long=0.9°

Inc	Pole Lat	Pole Long	A_{95}	Path Info.
33.2	56.7	179.0	6.1	
38.2	60.1	178.8	6.4	
43.2	63.8	178.6	6.8	θ
48.2	67.8	178.4	7.4	
52.8	72.0	177.9	7.9	IP
53.2	72.3	177.9	8.0	
58.2	77.5	177.0	9.0	
63.2	83.3	174.2	9.6	
68.2	89.3	95.3	10.5	
73.2	82.5	5.3	11.5	

Table 2b

Faroe Islands small circle path points Dec=8.0°, Inc=62.5°, pmag co-lat=47.2° Site Lat=61.8°, Site Long=353.0°

Dec	Pole Lat	Pole Long	Path Info.
348.0	70.7	199.9	
353.0	71.5	189.1	
357.9	72.0	177.9	IP
358.0	72.0	177.7	
3.0	71.9	166.8	
8.0	71.4	154.7	θ
13.0	70.4	144.0	
18.0	69.1	134.3	
23.0	67.5	125.5	
28.0	65.7	117.6	

Table 2c

Kyrgyzstan Tien Shan small circle path points Dec=14.6°, Inc=54.6°, pmag co-lat=55.5° Site Lat=40.7°, Site Long=76.2°

Dec	Pole Lat	Pole Long	Path Info.
354.6	83.0	295.3	
359.6	83.8	259.3	
4.6	82.8	224.2	
9.6	80.2	202.2	
14.6	76.9	189.6	θ
19.6	73.3	181.6	
21.6	72.1	177.4	‡
24.6	69.6	175.9	
29.6	65.9	171.4	
34.6	62.1	167.7	

Table 2d

China Tien Shan small circle path points Dec=54.5°, Inc=49.4°, pmag co-lat=69.8° Site Lat=40.23°, Site Long=75.25°

Dec	Pole Lat	Pole Long	Path Info.
54.5	45.1	160.3	θ
49.5	48.9	163.3	
44.5	52.7	166.5	
39.5	56.5	170.0	
34.5	60.3	174.0	
29.5	64.1	178.6	
24.5	67.7	184.2	
21.3	70.0	188.5	‡
19.5	71.3	191.3	
14.5	74.6	200.9	

For the Faroe Island and two Tien Shan results, the paleomagnetic co-latitude, which is the angle between the site and North Pole in the early Paleogene, defines the angular radii of the associated small circle paths. For the Sheppey data, the α95 values are listed for each step, whereas with the small circle paths the figure remains fixed. θ is the calculated pole, IP is the intersection point for the Faroe Island and Sheppey circles, ‡ is the nearest point along the Kyrgyzstan and China Tien Shan small circles to the Faroe–Sheppey circle path intersection point.

and ty15. The in situ mean (normal polarity corrected) is Dec=75.7°, Inc=66.3°, where α95=9.6° and k=21.4. Application of the tilt corrections, most sites within the succession have unique bedding attitudes, results in a slightly better clustering with Dec=54.5°, Inc=49.4°, where α95=7.7° and k=32.5. The resultant pole plots at 45.1°N, 160.3°E (Table 1b).

Such a large clockwise offset of the direction/apparent pole suggests that the rocks in the Tien Shan are again recording local vertical-axis rotations, although in this case in the opposite sense to that identified in the Kyrgyzstan part of the range. Therefore, because the China Tien Shan basalts almost certainly do not carry flattened inclinations, it should be possible to derive a reliable estimate of the site's paleomagnetic latitude/co-latitude ~59 Ma. Using the same procedure adopted for the Faroe Isles and Kyrgyzstan results allows a small circle with an angular radius of 59.8° to be constructed around the Tien Shan sampling location (Fig. 3b, Table 2d). Rotating the mean direction 33.2° counterclockwise brings the apparent pole to within 3.9° (<440 km) of the Faroe–Sheppey hybrid pole's position, which is much less than the A_{95} values associated with the China Tien Shan and hybrid poles (8.5° and 7.9° respectively).

3. Discussion

3.1. Hybrid pole to fix Eurasia

The Faroe–Sheppey hybrid pole proposal [10] thus appears to offer a robust solution for fixing Eurasia's site in the late Paleocene–early Eocene, quality data from two recently studied basalt sequences in Central Asia providing a strong positive test. The new pole eliminates the need to use the questionably reliable "old" data from the European North Atlantic Igneous Province [4]. The analysis also suggests that the inclination shallowing effect identified in numerous sedimentary rocks studies in various parts of Asia is likely due to depositional flow effects and/or sediment compaction. Some of the more radical proposals explaining the shallowing, including internal deformation of the stable Eurasia [21] and a long-lasting regionally-deformed magnetic field sitting over Asia [22], can probably now be discarded (see also Yan et al. [8]).

3.2. India–Asia collision at 55 Ma

It is widely considered that India collided with Eurasia around 55 million yrs ago [23–26]. However, there appears to be a problem with this assumption; India and Asia were nowhere near each other at this time (Fig. 4). Incidentally, the Faroe–Sheppey hybrid pole brings India and Asia closer together than any of the ENAIP poles, be they based on "old" result compilations [1–3] or new data [4]. It is very likely that following collision one or both continents experienced sub-regional shortening, subduction or sideways displacement, but this is not nearly enough to bridge Neotethys at 55 Ma. For instance, recent work aimed at deducing India's shape and size prior to its collision with Asia [27] has shown that extensions north of the craton ranged from ~950 km in the centre to ~500 km and ~600 km respectively at the Eastern and Western syntaxes (Fig. 4). Thus with a Paleocene/Eocene boundary-time collision, 1600–1800 km of Asian crust had to have been present between the southern edge of the Lhasa block and the stable Eurasia (north of the Tien Shan) all of which has subsequently been "removed". Although there is clear evidence indicating Asia shortening and extrusion [28], and possibly even continental subduction beneath northern Tibet [29], there still appears to be a sizeable amount of crust unaccounted for. A later India–Asia collision [10,30] is one of the simpler solutions to this conundrum.

3.3. Internal deformation of Cenozoic Asia

Paleomagnetic declination data are commonly used in tectonic studies of Asia, providing quantitative information on regional, sub-regional and localized deformation patterns (e.g., [31–33]). The new hybrid pole should

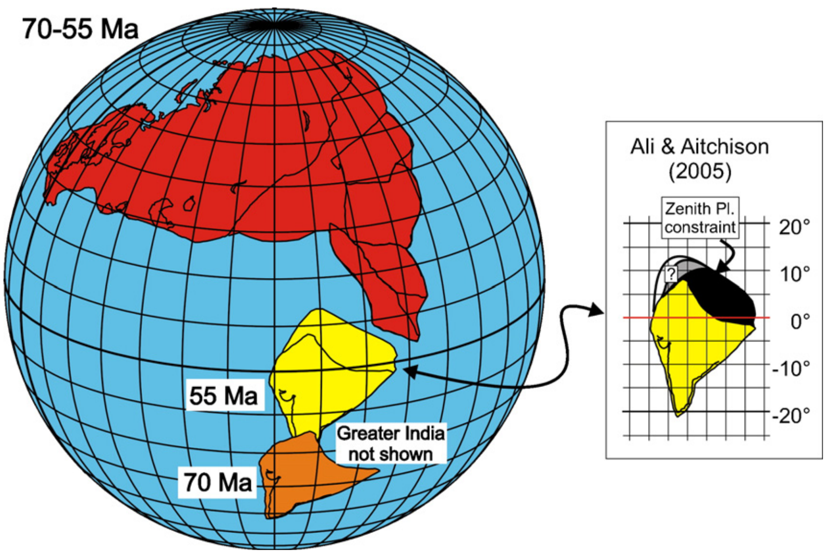

Fig. 4. Postulated position of Eurasia and India in the Late Cretaceous (70 Ma) and early Paleogene (55 Ma) plotted using the GMAP software program [38]. The stencil used to draw Eurasia ("Eurasiayoung.c97") has been modified slightly by extending Tibet south to include all of the ground north of the Yalung Tsangpo suture. Eurasia is fixed using the Faroe–Sheppey "hybrid pole", and Indochina is moved about 500 km northwest to its pre-extrusion site. Note that if the older ENAIP pole suites (e.g., [1,3,34]) are used to position Eurasia, Tibet is moved further north thereby widening Neotethys. The 70 and 55 Ma positions of Greater India [18] are based on Acton's [37] pole set. Note that two principal sources of error affect India's positioning. The first concerns the 95% confidence circle associated with each of the apparent poles, which Acton states as being 4.7° (i.e., ±520 km). The second type of error is associated with the geological time scale and India's velocity at specific times. In Geological Time Scale 2004 [39], age errors for the terminal Cretaceous and Paleocene are ±0.2 to ±0.3 Ma. Assuming India was then traveling at ~18 cm/yr, this error ranges between ±36 and ±54 km. Note also that if the Schettino and Scotese [34] data-base is used to fix India, the subcontinent is placed ~400 km further south at 55 Ma. The India-focused Galls (cylindrical) projection shows the sub-continent at 55 Ma with its postulated northern appendage [27].

prove useful, allowing the exact magnitude of rotations relative to the geographic spin axis and within Eurasia to be better constrained. Asia is often tacitly assumed to have undergone negligible motion in the Cenozoic, but all pole proposals (e.g., [1,3,4,10,34]) require some movement with estimates of clockwise rotation in southern Tibet varying between 10° and 21° since the start of the Eocene. For example, the hybrid pole implies that a lower Eocene formation in the middle of the Tarim Basin (say, 39°N, 82°E, Fig. 1) would have rotated 22° clockwise relative to the spin axis due to "stable" Eurasia's motion. Therefore, any local or regional-scale movements deduced from paleomagnetic data obtained from "deformed" Eurasia, for instance in extrusion-model studies, need to be examined in this context.

4. Conclusion

Limitations of the "stable" Eurasia paleomagnetic database (temporal and geographic coverage) is a major issue for those wishing to know the exact position of Earth's largest continental plate in the Cretaceous and Paleogene. Such uncertainty hampers the modeling of tectonic systems in a number of different parts of Asia, in particular the India collision and its subsequent aftermath. A novel solution was recently proposed [10] for 60–50 Ma which involved using paleomagnetic data from lower Eocene sedimentary rocks in SE England and upper Paleocene basalt flows from the Faroe Islands: the "hybrid" pole plots at 72.0°N, 177.9°E, where $A_{95}=7.9°$. A strong positive test of the proposal involved using paleomagnetic data from basaltic flows in the Tien Shan range, Kyrgyzstan [5]: the predicted paleolatitude was to within fractions of a degree identical to that preserved in the rocks (derived from the recorded inclination). Unfortunately, a drawback with that data-set is its large age error (±15 m.y. for rocks estimated to have formed ~50 Ma).

A recently published result [20] from Paleocene basalts in the China Tien Shan provides a powerful alternative for assessing the hybrid pole's validity. The direction has a relatively small α95 (7.5°), but critically the rocks have also been accurately dated using the Ar–Ar technique to ~59 Ma. The paleolatitude deduced for the site (30.2°N) is just a few degrees from that predicted by the hybrid pole (34.2°N). The direction obtained by Huang et al. [20] (declination = 54.5°) implies that the sequence they examined has rotated 33.2° clockwise relative to stable Eurasia. However, this is perhaps not surprising as the rocks are within a young-active intra-continental orogenic belt. It is also noted that others working in the Tien Shan have observed variable rotations, sometimes moderately large, in Cretaceous and Paleogene rocks from the range [35,36]. Whilst the hybrid pole [10] enhances considerably our knowledge of Eurasia's position 60–50 Ma, it unfortunately highlights the fact that the data-base for the other 135 million yrs of the Cretaceous and Cenozoic is still woefully poor.

The hybrid pole has inevitably led us to also examine its broader impact. Of particular interest is the commonly stated point that India collided with Asia at ~55 Ma. However reconstructing the past positions India (using the pole suite of Acton [37]) and Asia (based on the pole resulting from [10] and this study) indicates that the two continents were widely separated at this time. Tectonocists may in future wish to accommodate this information when modelling the system.

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