Northward Growth of the West Kunlun Mountains: Insight From the Age–Elevation Relationship of New Apatite Fission Track Data

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The Cenozoic collision between India and Asia promoted the widespread uplift of the Tibetan Plateau, with significant deformation documented in the Pamir Plateau and West Kunlun Mountains. Low-temperature thermochronology and basin provenance analysis have revealed three episodes of rapid deformation and uplift in the Pamir–West Kunlun Mountains during the Cenozoic. However, there is very little low-temperature thermochronology age–elevation relationship (AER) data on fast exhumation events in this area—especially in the West Kunlun Mountains—leading to uncertainty surrounding how these events propagated within and around the mountain range. In this study, we produced an elevation profile across granite located south of Kudi, Xijiang Province, China, to reveal its exhumation history. Apatite fission track AER data show that a rapid exhumation event occurred at ∼26 Ma in the southern West Kunlun Mountains. When combined with published data, we interpret that the initial uplift events related to the India–Asia collision began in the central Pamir, southern West Kunlun, and northern West Kunlun regions during the Late Eocene, Oligocene, and Middle Miocene periods, respectively. Therefore, the Cenozoic northward growth process occurred from south to north around West Kunlun.

Keywords: apatite fission track, age-elevation relationship, West Kunlun Mountains, Tibetan Plateau, deformation, uplift

INTRODUCTION

The Cenozoic collision between India and Asia formed the Tibetan Plateau (TP, Figure 1A), a series of intracratonic orogenic belts (Tapponnier et al., 2001; Royden et al., 2008), and induced regional climatic change (Raymo and Ruddiman, 1992). The onset ages of the India–Asia collision in the western Himalaya syntaxis (WHS), central Tibet and eastern Himalayan syntaxis (EHS) remain debated (Leech et al., 2005; Hu et al., 2016). The WHS is dominated by the Pamir Plateau, which is comprised of the northern Pamir, central Pamir, and southern Pamir (Figure 1B) domains. The northern Pamir has Asian affinity, whereas the central and southern Pamir regions have Cimmerian Gondwanan affinity (Burman and Molnar, 1993; Li et al., 2020). The West Kunlun Mountains (WK), situated in the southeastern Pamir, are divided into the southern West Kunlun (SWK) and
FIGURE 1  | (A) Location of the western Himalayan syntaxis (WHS) (modified from Tapponnier et al. (2001)). (B) Geomorphology and main faults in the Pamir–Southwestern Tien Shan. Red stars mark the main sites where magnetostratigraphy was performed in the southwestern Tarim and Tajik basins. Abbreviations are as follows: T, terranes; S., suture; F, fault; R, river; ZFT, zircon fission track age; ZHe, zircon (U–Th)/He age; AFT, apatite fission track age; AHe, apatite (U–Th)/He age; AK, Asku section; DA, Dashtijum section; PE, Peshtova section; BK, Baxbulak section; BT, Bora Tokay section; AK, Akiqiy section; OT, Oytag section; QM, Qimugen section; AT, Aertashi section; KY, Kekeya section; and LY, Keliyang section.)
GEOLOGICAL SETTING

The Pamir–WK is broadly salient and has been displaced northward over the Tarim–Tajik basins along the Main Pamir thrust system and Darvaz fault (Figure 1B). The Pamir–WK can be divided into four tectonic terranes: the NWK, the northern Pamir–SWK, the central Pamir–Songpan-Ganzi, and the Southern Pamir–Karakorum–Hidu Kush–Qiangtang, which are separated by the Kudi suture, Tanyamas-Karakax suture, and Rushan-Pshart-Jinsha suture, respectively (Figure 1B). The former two terranes have affinity to Asia, whereas the latter two terranes previously split away from the Gondwanan (Burtman and Molnar, 1993; Li et al., 2020). The southwestern Tien Shan was situated north of the Pamir–WK prior to the shortening of strata during the Cenozoic, with estimates of shortening between both domains ranging between ~50 and 100 km (Chen et al., 2018; Li et al., 2020) and ~300 km (Burtman and Molnar, 1993).

The WK is bordered by the Tarim Basin to the north, the Pamir Plateau to the northwest, and the Songpan-Ganzi terrane to the south. It is a mountainous region ~700 km long, ~100–130 km wide, and contains peaks up to ~7,600 m high. The Tarim Basin has an elevation of <1,500 m, while the frontal orogenic fold belt between the Tarim Basin and the Tikklik fault has an elevation of 1,500–2,500 m. To the south of the Tikklik fault, the WK itself has an elevation of 3,000–6,000 m. The WK can be divided into the northern and southern parts by the Kudi suture (Figure 1B), which formed due to the closure of the Proto-Tethys Ocean (Matte et al., 1996). The WK initially formed during the Paleozoic-Mesozoic and experienced a complex strike-slip to compressive evolution (Yin and Harrison, 2000; Arnaud et al., 2003; Laborde et al., 2019). The WK reached its current elevation due to reactivation of pre-existing faults during the Cenozoic India–Asia collision (Matte et al., 1996; Yin and Harrison, 2000; Jiang et al., 2013; Laborde et al., 2019).

To the north of the WK, the Tarim Basin contains extensive Mesozoic-Cenozoic deposits and has an average thickness of ~1,200 m. Today, the Tarim Basin is an endorheic basin surrounded by mountain ranges: the Pamir–WK to the southwest, the Altyn Tagh Mountains to the southeast, and the Tien Shan to the north. These ranges previously provided abundant sediment that infilled the Tarim Basin, with the Pamir–WK having been the main sedimentary provenance for the SW Tarim Basin during the Mesozoic–Cenozoic, especially during the Cenozoic (Jiang and Li, 2014; Li et al., 2021). The Mesozoic strata in the SW Tarim Basin include Jurassic (Shalitashi, Kansu, Yangye and Kuzigongsu Formations) and Cretaceous (Kezilesu and Yengisar Groups) sediments (Sobel, 1999), and the Cenozoic strata include the Kashi Group (Aertashi, Qimueng, Kalatar, Ulegen and Bashibuke Formations), Wuqia Group (Keziluoyi, Anjuan and Pakabuleke Formations), Artux Formation and Xiyu Formation (Jia et al., 2004; Liu et al., 2017a).

SAMPLING AND METHODS

Geological mapping and sampling were performed over several years in the WK in collaboration with the China Geological Survey. Survey routes were situated near the G219 highway, which runs from Xinjiang to Tibet, and granite samples were collected from southern Kudi. From north to south, this area consists of the NWK, SWK, and Songpan-Ganzi (Figure 2). The NWK includes Carboniferous and Mesoproterozoic rocks of the Changcheng System and Silurian and Ordovician granites. The SWK contains Mesoproterozoic rocks of the Changcheng System, alongside granite of various ages, and other deformed rocks. The Songpan-Ganzi terrane only shows exposed Silurian rocks. A topographic profile from the Songpan-Ganzi to the NWK shows that these three terranes attain maximum elevations exceeding 4,500, 3,000, and 2,700 m (Figure 3). The study regions contain several types of granite. Five samples (KDW52, KDW55, KDW60, KDW61, and KDW62) were collected from a...
FIGURE 2 | Geological map of the corridor along the Xinjiang-Tibet Road from Akaz to Heiqia. Abbervations for stratigraphic units are given by region. Northern West Kunlun: Pt2, Middle Proterozoic; Jxbb, segment B in the Bochatetage Formation of the Middle Proterozoic Jirexian System; C1T, Carboniferous Talong Group; C1Y, Carboniferous Yishake Group; C2K, Carboniferous Kuerliang Group; Є-Ox, Cambrian–Ordovician Xiheti Group; SγβK, Silurian biotite adamellite; SγβKc, segment C in Silurian biotite adamellite; and OγβKc, segment C in Ordovician coarse monzogranite. Southern West Kunlun: Q, Quaternary; ChSta, segment A of the Saitula Group of the Middle Proterozoic Changchengian System; C1, Carboniferous Talong Group; Pz1, Kudi ophiolitic mélange; Pt2, Middle Proterozoic gneissic biotite monzogranite; C1γηδμ, Cambrian diabase; Oηδc, Ordovician medium-grained (Continued)
Triassic (T\textsubscript{v8b}) intrusion between its highest (4,814 m) and lowest (3,540 m) points (Figures 2, 3 and Table 1).

All granite samples were crushed and pulverized, and constituent minerals were concentrated by using standard magnetic and density separation techniques. Individual apatite grains were handpicked from the concentrates and used for fission track dating via the external detector method, following the procedures documented in our previous publication (Liu et al., 2017b). Initially, apatite grains were mounted and polished to expose the centers of as many grains as possible and were then immersed in 5.5 N H\textsubscript{3}NO\textsubscript{3} for 20 s at 21°C to reveal natural fission tracks. Fission track sample mounts, age standards (Fish Canyon and Durango) and IRMM540R dosimeter samples were irradiated together in a thermalized reactor located at Oregon State University, United States, using a thermal neutron fluency of $1.0 \times 10^{16}$ n cm\textsuperscript{-2}. U-free muscovite external detectors were etched in 40% HF for 40 min at 20°C to reveal their induced fission tracks. Fission tracks were counted on a Zeiss microscope at the Chinese Academy of Geological Sciences, China, using an Autoscan system (produced in

| Sample | Location: Long. (E) Lat. (N) | Elevation (m) | N | Rho-S ($10^{15}$ cm$^{-2}$) N\textsubscript{s} | Rho-I ($10^{15}$ cm$^{-2}$) N\textsubscript{i} | Rho-D ($10^{15}$ cm$^{-2}$) N\textsubscript{d} | $P(\chi^2)$ (%) | Central age (Ma) ($\pm\sigma$) | Mean D\textsubscript{par} ($\mu$m) |
|--------|-----------------------------|--------------|---|-------------------------|-------------------------|-------------------------|----------------|-----------------|----------------|
| KDW52  | 36.69767° 77.01437°         | 4,814        | 23 | 1.955 (98)             | 13.047 (654)           | 12.5 (16,059)           | 89.25         | 25.5 ± 3.1     | 1.27           |
| KDW55  | 36.69469° 77.01894°         | 4,445        | 24 | 2.568 (212)            | 20.376 (1,682)         | 13.3 (16,059)           | 0.01          | 26.7 ± 3.2     | 1.36           |
| KDW60  | 36.70085° 77.04183°         | 3,869        | 23 | 2.554 (190)            | 20.637 (1,535)         | 14.0 (16,627)           | 0.06          | 25.8 ± 3.3     | 1.36           |
| KDW61  | 36.7045° 77.04486°          | 3,715        | 22 | 1.776 (148)            | 21.282 (1,773)         | 13.9 (16,627)           | 4.73           | 16.4 ± 2.0     | 1.26           |
| KDW62  | 36.7036° 77.04749°          | 3,540        | 24 | 2.592 (231)            | 31.026 (2,765)         | 12.9 (16,059)           | 36.69         | 14.8 ± 1.4     | 1.38           |

The zeta ($\zeta$) value is 272.78 ± 15.99. Abbreviations are as follows: N, number of individual grains dated; Rho-S, spontaneous track density ($\times 10^{15}$ tracks cm$^{-2}$); N\textsubscript{s}, number of spontaneous tracks counted; Rho-I, induced track density in external detector (muscovite) ($\times 10^{15}$ tracks cm$^{-2}$); N\textsubscript{i}, number of induced tracks counted; Rho-D, induced track density in external detector adjacent to dosimeter glass ($\times 10^{15}$ tracks cm$^{-2}$); N\textsubscript{d}, number of tracks used to determine Rho-D; $P(\chi^2)$, ($\%$), Chi-square probability (Galbraith, 1984); Mean D\textsubscript{par}, arithmetic mean diameter of fission-track etch figures parallel to the crystallographic c-axis.
Australia) in manual mode, set to a magnification of ×1,000. The zeta (ζ) value of 272.78 ± 15.99 was obtained using Durango and Fish Canyon apatite standards (Hurford and Green, 1983; Naeser and Cebula, 1985). More than 20 grains were chosen from each sample. All ages were determined to be within an error of 1σ using the computer code “Trackkey” (Dunkl, 2002).

RESULTS

Between 22 and 24 grains were analyzed for AFT in each sample, and the results are listed in Table 1 and shown in Figure 4. For this measurement, the value of Zeta (ζ) is 272.78 ± 15.99. Three samples (KDW55, KDW60 and KDW61) show low AFT P (χ²) values (<5%), although the highest and lowest elevation samples (KDW52 and KDW62) show high P (χ²) values (>5%) (Table 1). The AFT central ages are 25.5 ± 2.6, 26.7 ± 2.8, 25.8 ± 3.3, 16.4 ± 2.0, and 14.8 ± 1.4 Ma for KDW52, KDW55, KDW60, KDW61, and KDW62, respectively. The mean Dpar varied from 1.26 to 1.38 μm. Because the AFT ages determined for these samples are younger than 30 Ma, we did not measure the full track lengths.
Figure 5 shows AER data using the central ages. The ages of samples with the three highest elevations are near ~26 Ma (KDW52, KDW55 and KDW60), while the ages of the two low-elevation samples are near ~15–16 Ma (KDW61 and KDW62). A clear transition point in AER data can be seen in Figure 5 at ~26 Ma.

**DISCUSSION**

**Rapid Oligocene Uplift in the Southern West Kunlun Mountains**

Low-temperature thermochronological data are highly effective for deciphering the cooling history of a region, with techniques including apatite (U-Th)/He (AHe, ~30–120°C), apatite fission track (AFT, ~60–110°C), zircon (U-Th)/He (ZHe, ~130–200°C), and zircon fission track (ZFT, ~220–260°C) (Reiners et al., 2005; Guenthner et al., 2013). The cooling rates, especially from the AER data, derived from these minerals have been widely used to identify rapid uplift events in the eastern (Wang et al., 2012; Tian et al., 2013; Zhang et al., 2016; Liu-Zeng et al., 2018; Cao et al., 2019; Replumaz et al., 2020), northern (Liu et al., 2017b, 2021; Wang et al., 2017; Zhuang et al., 2018; Lin et al., 2021), and western (Wang et al., 2003; Amidon and Hynek, 2010; Sobel et al., 2011; Cao et al., 2013; Thiede et al., 2013; Cao et al., 2015; Li et al., 2019) Tibetan Plateau. Unfortunately, the rapid cooling rates derived from AER data do not always imply rapid exhumation rates (Stüwe et al., 1994; Burbank, 2002). However, the break-in-slope point or zone in an AER should record a significant tectonic transformation (Braun, 2002; Valla et al., 2010), which is used to correlate with a rapid uplift event within the Tibetan Plateau (Zheng et al., 2006; Oumi et al., 2010; Zheng et al., 2010; Lease et al., 2011; Wang et al., 2012; Tian et al., 2015). In this study, the three lowest-elevation samples yielded a mean exhumation rate of ~0.041 km/Ma. The three highest-elevation samples yield very similar central ages of ~26 Ma (Figure 5), indicating that the adjacent area has undergone rapid exhumation at ~26 Ma. As our samples were collected from the SWK (Figure 1B), the SWK is interpreted to have undergone rapid uplift at ~26 Ma, followed by a period of slow uplift that continued to at least ~15 Ma (Figure 5).

Based on source-to-sink theory, sedimentary provenance analysis in a basin can effectively decipher the evolutionary history of adjacent ranges (Fedo et al., 2003; Najman, 2006; Kimbrough et al., 2015; Koshnaw et al., 2018; Coutts et al., 2019; Nordsvan et al., 2020; Resentini et al., 2020). Basin analysis has been applied to several mountain front in the Pamir–WK region, which has constrained the evolutionary history of its adjacent ranges. The dominance of Cenozoic northward-directed paleocurrents in the SW Tarim Basin indicates that the basin sediments were mainly derived from its southern margin (Sobel, 1999; Bershaw et al., 2012; Cao et al., 2014; Zhang et al., 2019; Li et al., 2021). Interestingly, an ~45 Ma peak in detrital zircon U/Pb ages is documented only in the central Pamir and first appears in Eocene strata in the SW Tarim and Tajik basins (Blayney et al., 2016; Sun et al., 2016; Wang et al., 2019; Zhang et al., 2019; Sun et al., 2020; Wang et al., 2021). Previous documents indicated that this magmatic activity represented the Late Eocene rapid uplift in the central Pamir region, based on late Eocene detrital apatite fission track ages and regional tectonic movements (Wang et al., 2019; Zhang et al., 2019; Wang et al., 2021). Moreover, detrital zircons with an age peak of ~45 Ma are absent in sedimentary rocks that formed at ~26 Ma in the Oyitag and after ~26.5 Ma in the Aertashi sections of the SW Tarim Basin (Figure 6; Blayney et al., 2016; Sun et al., 2016), indicating that the influx of sediments from the central Pamir region was hindered by the growth of the mountains to the northern side of the basin. Based on our new data, we interpret that the SWK experienced rapid uplift at ~26 Ma, which restricted sediment flux into its northern basins.

Both the low-temperature thermochronology performed herein and previous basin sedimentary provenance analyses confirm that the SWK experienced rapid uplift at ~26 Ma, which restricted sediments sourced from central Pamir region from being transported into its northern basins. Paleomagnetic data show an abrupt increase in mean magnetic susceptibility at ~26 Ma in the Baxbulak section of the Alai Valley, although this has previously been interpreted as recording tectonic activity in the southwestern Tian Shan (Tang et al., 2015). Nonetheless, this rapid exhumation event (~25–16 Ma) is also documented in the northern Pamir region (Amidon and Hynek, 2010), indicating that this event may record regional-scale movement on the northwestern Tibetan Plateau.

**Cenozoic Northward Growth of West Kunlun Mountains**

The WK is divided into southern and northern domains, with the former extending to the northern Pamir region (Figure 1B). Sedimentary provenance analysis indicates that the WK and northern Pamir region had certain paleoelevations prior to the Cenozoic (Cao et al., 2015; Blayney et al., 2016; Li et al., 2020), which supports rapid uplift in the northern Pamir region during the late Paleocene–early Eocene (~50–40 Ma) (Amidon and Hynek, 2010; Carrapa et al., 2015; Chen et al., 2018). As the sedimentary provenance in the SW Tarim and Tajik basins did not change between the Late Cretaceous and the Early Eocene, the topography of the nearby ranges must also not have changed during this time. The first quasi-synchronous rapid uplift of the central Pamir region occurred in the Late Eocene (40–30 Ma), and provided a new sediment flux into the SW Tarim and Tajik basins (Blayney et al., 2016; Wang et al., 2019; Zhang et al., 2019; Sun et al., 2020; Wang et al., 2021), although this occurred at the earliest time of ~47 Ma in the Oytag section of the Tarim Basin (Sun et al., 2016). The second regional-scale rapid uplift in the SWK (this study) and northern Pamir region (Amidon and Hynek, 2010) occurred during the Oligocene; this lasted at least ~9 Ma (from 25 to 16 Ma) in the northern Pamir region, but there are no geochronological data to constrain its duration in the SWK. The >1,000-km-long Karakorum Fault developed during this Oligocene uplift event (Lacassin et al., 2004; Li et al., 2007; Valli et al., 2007; Valli et al., 2008) and subsequently played a vital role in the evolution of the WHS (Cowgill, 2010). Finally, a third episode of rapid uplift began in...
FIGURE 6 | U-Pb detrital zircon data shown as normalized kernel density plots for rocks from the Oytag (Sun et al., 2016) and Aertashi (Blayney et al., 2016) sections in the SW Tarim Basin. The shaded bar represents the populations diagnostic of the central Pamir provenance with a detrital zircon U-Pb peak age of ~45 Ma. The ages in the brackets after the sample ID represent the sedimentary ages. N indicates the number of measured detrital zircon grains.
the WK and northern Pamir during the Middle Miocene, with
this event continuing to the present day and shaping the current
landscape (Cao et al., 2013; Thiede et al., 2013; Cao et al., 2015;
Blayney et al., 2019). Our new data combined with published results show that at least
three rapid uplift events occurred in the Pamir–WK during the
Cenozoic (Figure 7), but how did each of these events influence the
tectonic evolution of the WK? The ∼45 Ma peak of detrital zircon
U/Pb ages indicates that the central Pamir region experienced the first
uplift event, although no equivalent ages are recognized in the WK,
despite its northward extension (i.e., the northern Pamir) recording
this event. Moreover, if the WK had experienced this uplift at this
time, the sediments from the central Pamir region would not have
been deposited in the SW Tarim Basin. Therefore, we believe that the
first uplift event only took place south of the WK. Our AFT data
confirm that the second uplift event occurred in the SWK, which
restricted sediments derived from the central Pamir region from
entering the SW Tarim Basin. Prior to this study, no Oligocene
thermochronological data were reported from the NWK, which
implies that this second major uplift event did not affect the
NWK. Furthermore, while thermochronological data confirm that
the third uplift event occurred in the NWK (Sobel and Dumitru, 1997;
Sobel et al., 2011; Chapman et al., 2017) and northern Pamir region
(Sobel et al., 2011; Thiede et al., 2013; Figures 1, 7), no previous data
have shown that this event affected the SWK. Our data from the Kudi
profile indicate that the phase of relatively slow exhumation lasted
from ∼26 to ∼15 Ma (Figure 5). Furthermore, as the SWK
currently has higher elevation than the NWK (Figure 7), the
southern domain likely experienced a prolonged period of uplift
than the northern domain. Therefore, we suggest that the SWK
possibly also experienced the third documented uplift event. Based
on these data, three Cenozoic uplift events should first occur to the
south of the WK, SWK, and NWK during the Eocene, Oligocene,
and Mid-Miocene (Figure 7). Therefore, northward growth should
take place around the WK, possibly caused by the stepwise growth
(Tapponnier et al., 2001) or continuous deformation (Molnar et al.,
1993) of the Tibetan Plateau.

Sedimentary provenance analysis in the SW Tarim Basin also
supports the interpreted northward growth of the WK. Detrital
zircons with age peaks of ∼45 Ma are absent in sedimentary rocks
that formed at ∼26–15 and ∼14–11 Ma in the Aertashi section of
the SW Tarim Basin (Figure 6; Blayney et al., 2016), which
indicates that sediments from the central Pamir region could not
freely enter its northern basin. The reason for this limited
movement is most likely due to being restricted by uplift of the
WK. These events are shown in Figure 8 as a tectonic model
for the WK. During the Late Cretaceous, the central
Pamir–Songpan–Ganzi region had not experienced uplift,
whereas the WK had a greater elevation, allowing the
paleorivers (e.g., the Pishan River, the Yarkang River and
others) to erode headward toward the Songpan–Ganzi terrane.
During the Eocene, the Paratethys Ocean transgressed into and
retreated from the Tarim Basin, and the central Pamir region
experienced initial Cenozoic uplift, which allowed the paleorivers
(e.g., the Pishan River and the Yarkang River) to supply new
detrital zircon grains with ∼45 Ma peak ages. During the
Oligocene, the SWK experienced abrupt uplift, which
restricted the sedimentary flux from the central Pamir region

FIGURE 7 | Tectonic events that have affected the West Kunlun Mountains. Yellow, red and green lines indicate the maximum, average and minimum elevations of
selected area, which showing in the Figure 1B with red frame. Pick dots and dots with error bars indicate the elevations and AFT cooling ages from Chapman et al.
(2017). Red dots and dots with error bars indicate the elevations and AFT cooling ages from Thiede et al. (2013). Green dots and dots with error bars indicate the
elevations and AFT cooling ages from Sobel et al. (2011). Blue dots and dots with error bars indicate the elevations and AFT cooling ages from Cao et al. (2013).
Yellow dots and dots with error bars indicate the elevations and AFT cooling ages from Li et al. (2019). Black dots and dots with error bars indicate the elevations and AFT
cooling ages from this study.
into the SW Tarim Basin. From the middle Miocene to the present day, the NWK and SWK both experienced abrupt uplift, which restricted the transport of eroded material from the central Pamir region into the Tarim Basin, although the head of the paleo-Yarkang River eroded through the central Pamir region at \(\sim 26\)–15 and \(\sim 14\)–11 Ma.

**CONCLUSION**

1) The age–elevation relationship (AER) of the apatite fission track (AFT) shows that rapid exhumation occurred at \(\sim 26\) Ma in southern West Kunlun.

2) Combining these data with those of previous studies shows that West Kunlun and its adjacent region experienced northward initial Cenozoic growth during the Late Eocene, Oligocene, and Middle Miocene in the central Pamir, southern West Kunlun, and northern West Kunlun regions, respectively.

**DATA AVAILABILITY STATEMENT**

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

**AUTHOR CONTRIBUTIONS**

This manuscript was designed and written by DL. This manuscript was supported by funds from DL, HL, and JP. The apatite fission track data were measured by YW. Other co-authors attended the field and figure work, including CG, MB, YZ, PW, FL, and SW.

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