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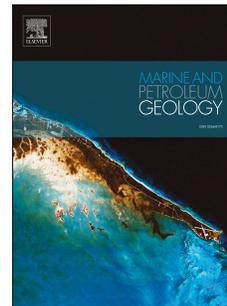
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38 **Abstract**

39 The previous understanding of Tian Shan's lithospheric architecture can be summarized into
40 three models: unidirectional underthrusting, bidirectional underthrusting, and mantle upwelling.
41 These models make distinctive predictions regarding the migration and subsidence histories of
42 the foreland basins on either side of the range. Seismic profiles crossing both foreland basins
43 document their migration and subsidence history. We analyze a seismic profile across the
44 Southern Junggar foreland basin (SJFB) to the north of the range, which demonstrates that the
45 basin migrated northward at ~ 3.1 mm/yr during 22–16 Ma. Combining this with previously

46 known migration rates of the Northern Tarim foreland basin (NTFB) to the south of the range,
47 we constrain the migration of these two foreland basins relative to their basements. We then
48 employ an elastic plate model to simulate the subsidence profiles across these two basins at ~20
49 Ma, 13-16 Ma, ~5 Ma, and 0 Ma constrained by back stripping well log data and seismic records
50 of the basin onlaps. Our modeling reveals the propagation rates of the southern and northern Tian
51 Shan thrust wedges and the evolution of their topographic loads. Our analysis and modelling
52 demonstrate that the NTFB has the characteristics of a retro-foreland basin, whereas the SJFB
53 resembles a pro-foreland basin during early-middle Miocene times. This suggests that the Tian
54 Shan's growth during this period was dominated by underthrusting of the Junggar lithosphere.
55 Furthermore, our analysis and modelling reveal a convergent pattern between the Tarim
56 lithosphere and the Tian Shan changed from lithospheric indentation to lithospheric subduction
57 after the middle Miocene, as the plate setting of the NTFB and SJFB changed. The Tian Shan
58 had begun to uplift before the middle Miocene, with the orogen's height reaching half of its
59 present elevation before the late Miocene.

60 **Keywords:** Tian Shan, Foreland basin, Subsidence modelling, Seismic profiling, Lithospheric
61 architecture

62 **1 Introduction**

63 The Asian continent underwent significant intra-continental deformation in the late Cenozoic
64 as a result of convergence between the Indian and Asian continents, including the modern Tian
65 Shan (Fig. 1). Although this understanding is widely accepted, there is still a debate over the
66 intra-continental Tian Shan orogen's deep architecture (e.g. Makeyeva et al., 1992; Zhao et al.,
67 2003; Lei and Zhao, 2007; Zhang et al., 2020; Table S1 in the supplementary material). As the
68 largest intra-continental orogenic belt on Earth, the modern Tian Shan is a doubly vergent thrust

69 belt formed by the rejuvenation of the Paleozoic collisional orogenic belt triggered by the
70 ongoing India-Eurasia collision (Molnar and Tapponnier, 1975; Windley et al., 1990; Hendrix et
71 al., 1992; Yin et al., 1998; Dumitru et al., 2001). The understanding of the deep lithospheric
72 architecture of the orogeny, based on geophysical investigations (Table S1), can be summarized
73 in terms of three models (Fig. 2): (1) The unidirectional underthrusting of the Tarim lithosphere
74 beneath the Tian Shan (Zhao et al., 2003; Steffen et al., 2011; Gilligan et al., 2014); (2) the
75 bidirectional underthrusting of the Tarim and Junggar lithospheres (Li et al., 2016a; Lü et al.,
76 2019); and (3) mantle upwelling caused by small-scale mantle convection in the upper mantle or
77 the delamination of the thickened lithosphere (Roecker et al., 1993; Lei and Zhao, 2007; Li et al.,
78 2009). The topographic uplift of the modern Tian Shan induced flexural subsidence in the
79 Northern Tarim and the Southern Junggar blocks, forming a typical intra-continental orogenic
80 belt-foreland basin system (Lu et al., 1994; Jia et al., 1997; Wang et al., 2001a; Qi et al., 2013).
81 The sedimentary infill of the Northern Tarim foreland basin (NTFB) and the Southern Junggar
82 foreland basin (SJFB) can be utilized as sources of insights into crustal shortening and
83 topographic growth of the Tian Shan (Wang et al., 2013; Li et al., 2019; 2020; 2022a). The three
84 models of the Tian Shan lithospheric architecture make distinctive predictions for the migration
85 and tectonic subsidence of the foreland basin systems according to the foreland basin-mountain
86 building theories (Johnson and Beaumont 1995; Naylor and Sinclair, 2008) (Fig. 2).

87 Although geophysical exploration provides a possible current lithospheric architecture of the
88 Tian Shan, the orogen's inferred geodynamic evolution from the modern lithospheric architecture
89 can be tested using multiple disciplines. The middle and eastern segments of the Tian Shan lack
90 exposures of late Cenozoic synorogenic magmatic rocks (Charvet et al., 2011). The Tian Shan
91 also lacks petrological and geochemical evidence reflecting subduction polarity of the Cenozoic

92 Tarim and Junggar lithospheres and the orogeny's geodynamic pattern, such as records of the
93 residual oceanic fore-arc basins, because the orogen did not undergo a transition from oceanic-
94 continental subduction to continental collision during the Meso-Cenozoic period (Jolivet et al.,
95 2010; Jepson et al., 2018; Morin et al., 2019). Furthermore, Cenozoic sedimentary infill
96 composition, provenance, and deformation styles of the shortening structure in the NTFB and
97 SJFB are very similar (Lu et al., 1994; Li et al., 2004; Bian et al., 2010).

98 In the last 40 years, geologists have extensively studied the sedimentary sequences and
99 subsidence history in foreland basins (e.g., Lyon-Caen and Molnar, 1985; Homewood et al.,
100 1986; Johnson and Beaumont, 1995; Simoes and Avouac, 2006), and they have discovered that
101 in orogenic belt-foreland basin systems, pro-foreland basins over underthrust lithosphere and
102 retro-foreland basins over overriding plates contrast markedly in terms of their stratigraphic
103 architecture, migration and subsidence histories (Johnson and Beaumont 1995; Naylor and
104 Sinclair, 2008). Pro-foreland basins are characterized by: (1) Stratigraphic onlap onto the
105 cratonic margin at a rate (V_{O-P}) equal to the sum of the plate convergence rate (V_C) and the
106 propagation rate of thrust wedge (V_{P-P}); (2) accelerating tectonic subsidence driven primarily by
107 the translation of the basin fills towards the mountain belt (Fig. 3). In contrast, retro-foreland
108 basins are characterized by: (1) relatively little stratigraphic onlap driven only by the growth of
109 the retro-wedge ($V_{O-R} = V_{P-R}$); (2) A constant tectonic subsidence rate during the growth of the
110 thrust wedge, with zero tectonic subsidence during the steady-state phase (Fig. 3). Hence, we can
111 test the lithosphere's subduction polarity and convergence rate by interpreting the basin fill
112 architecture and subsidence (e.g., Lyon-Caen and Molnar, 1985; Simoes and Avouac, 2006;
113 Sinclair and Naylor, 2012). According to Tian Shan's unidirectional underthrusting model, the
114 foreland basin on one side of the range should be characteristic of a pro-foreland basin, while the

115 foreland basin on the counterpart should conform to the characteristics of a retro-foreland basin.
116 The bidirectional underthrusting model, however, predicts that the foreland basins on both sides
117 of the range could be characteristic of the plate setting of a pro-foreland basin. Finally, the
118 mantle upwelling model predicts that the subsidence process of the foreland basins on both sides
119 was decoupled from the topographic evolution of the Tian Shan (Fig. 2), and a positive dynamic
120 topography should be recognized in the range. However, the subsidence process and sedimentary
121 successions in the NTFB and SJFB, as typical foreland basins, are coupled with the growth
122 history of the Tian Shan (Lu et al., 1994; Wang et al., 2013), and there is regional isostasy
123 compensation beneath the Tian Shan according to the flexural and rheological modeling (Jiang,
124 2014). Therefore, the mantle upwelling model is not supported by the evolution of the NTFB and
125 SJFB.

126 The NTFB and SJFB are the important petroliferous basins in western China, so numerous
127 high-quality seismic profiles have been acquired for hydrocarbon exploration in these two basins
128 (e.g., Jia et al., 1997; Wang et al., 2018), providing scientific insights into the migration and
129 subsidence histories of the basins. Understanding of the geodynamic context of the foreland
130 basins in terms of it being a retro- or pro-foreland basin also aids prediction of source rock
131 maturation, and potentially reservoir architecture (Bourrouilh et al., 1995; Naylor and Sinclair,
132 2008; Allen and Allen, 2013). Magnetostratigraphic studies (e.g., Sun et al., 2004; Huang et al.,
133 2006; Charreau et al., 2006; 2009; Lu et al., 2010; Zhang et al., 2014) provide reliable
134 chronological constraints on the foreland strata in these basins. Li et al. (2019) constrained the
135 relative migration rate of the forebulge of the NTFB relative to its basement by analyzing a
136 ~353-km-long seismic profile (BB' in Fig. 1) across the basin.

137 In this contribution, we use the stratigraphic geometries from a ~141-km-long seismic
138 profile (AA' in Fig. 1) crossing the SJFB to obtain the northward migration rate of the basin to
139 its basement and decipher its stratal architecture. The relative migration process of the foreland
140 basins on either side of the Tian Shan was constrained by combining the migration rates of the
141 NTFB and SJFB. Using back stripping based on the sedimentary sequences imaged by the two
142 seismic profiles, we further obtain the tectonic subsidence profiles across the two foreland basins
143 in the late Cenozoic times. Finally, we use a numerical elastic model to simulate and constrain
144 the controls on these subsidence profiles. The propagation rates of the southern and northern
145 Tian Shan wedges, as well as the evolution of their topographic loads in the late Cenozoic are
146 revealed by our modelling. The comparison between the NTFB and SJFB migration and
147 subsidence characters reveals their plate settings, and suggests a possible switch of subduction
148 polarity of the Tarim and Junggar lithospheres beneath the Tian Shan's middle segment in the
149 late Cenozoic.

150 **2 Geological backgrounds**

151 The ancestral Tian Shan orogen formed during the Paleozoic through the accretion of several
152 island arcs and collision of continental blocks (Burtman, 1975; Windley et al., 1990; Xiao et al.,
153 2013), with large-scale dextral strike-slip occurring in the late Carboniferous–Permian
154 (Bazhenov et al., 1999; Laurent-Charvet et al., 2003; Wang et al., 2007; He et al., 2021a). In the
155 Mesozoic, the Tian Shan was reactivated in response to a series of Cimmerian collisions (e.g.,
156 the collisions of Qiangtang, Lhasa, and Karakorum blocks with Eurasia) occurring along the
157 southern Eurasia margin (e.g., Jolivet et al., 2010; Jepson et al., 2018; Morin et al., 2019). In the
158 late Cenozoic, the Tian Shan rejuvenated as an intra-continental orogen with high topography,
159 caused by the far-field effect of the ongoing India-Eurasia collision (Molnar and Tapponnier,

160 1975; Yin et al., 1998; Dumitru et al., 2001; De Grave et al., 2007). The Tian Shan uplifts
161 significantly in the late Cenozoic attested by low-temperature thermochronology (e.g., Hendrix
162 et al., 1992; Dumitru et al., 2001; Sobel et al., 2006; Yu et al., 2014; Chang et al., 2017a; Wang
163 et al., 2023). The shortening structures within the folding and thrusting belts on the north and
164 south piedmonts of the Tian Shan's middle segment (Fig. 1) reflect the late Cenozoic horizontal
165 convergence between the Tarim and Junggar blocks, and that the Tian Shan underwent doubly
166 vergent thrusting over the Tarim and Junggar lithospheres (e.g., Lu et al., 1994; Deng et al.,
167 1999; Hubert-Ferrari et al., 2007; Lu et al., 2010; Wang et al., 2011; Li et al., 2012). Geophysical
168 surveys indicate that the Tarim lithosphere dips to the north beneath the middle segment of the
169 Tian Shan (e.g., Zhao et al., 2003; Lü et al., 2019) and even subducts to mantle depths (Sun et
170 al., 2022b), and they attest that the underthrusting of the Tarim lithosphere produced the uplift of
171 the range. GPS measurements and seismicity also indicate present-day growth of this orogen and
172 an NNW-trending convergence between the Tarim and Junggar blocks (Fig. 1) (Zubovich et al.,
173 2010; Shen and Wang, 2020). The contrast between the Quaternary shortening rate and the
174 denudation rate in the eastern segment of the Tian Shan shows that crustal thickening outpaced
175 denudation and sediment outflux by a factor of ~10, indicating that the range remains in a
176 transient state of topographic growth (Charreau et al., 2023). Numerous intermontane basins
177 were created by a post-orogenic phase of transtensive deformation during the Permian to Late
178 Triassic (Jolivet et al., 2010). These basins are still partially preserved from Late Triassic to
179 present, which caused a relatively low elevation in the center of the modern Tian Shan (Fig. 1)
180 (Charreau et al., 2017).

181 The upliftment of modern Tian Shan above the Paleozoic and Mesozoic strata caused
182 flexural subsidence of the NTFB and SJFB (Fig. 1; Yang and Liu, 2002) and formed the

183 Cenozoic foreland basin system (Lu et al., 1994; Jia et al., 1997; Wang et al., 2001a; Qi et al.,
184 2013; Li et al., 2016b). The NTFB in Tian Shan's south piedmont has a maximum thickness of
185 ~7 km of Cenozoic foreland strata, while the SJFB has a maximum thickness of ~5 km (Fig.
186 1)(Li et al., 1996; Wang et al., 2013; Li et al., 2019; 2022b).

187 The Cenozoic sedimentary sequences in the NTFB include the Kumugeliemu, Suweiyi,
188 Jidike, Kangcun, Kuqa, and Xiyu Formations in ascending order from older to younger (Zhang et
189 al., 2004). Li et al. (2019) correlated the seismic reflectors in our profile across the basin with the
190 magnetostratigraphic studies in the southern flank of the Tian Shan (Huang et al., 2006; Charreau
191 et al., 2009; Zhang et al., 2014) and dated the bottom of the Jidike, Kangcun, Kuqa, and Xiyu
192 Formations as ~26.3 Ma, ~13.4 Ma, ~5.3 Ma, and ~1.7 Ma, respectively (Fig. 4). Cenozoic strata
193 in the SJFB comprise the Ziniquanzi, Anjihaihe, Shawan, Taxihe, Dushanzi, and Xiyu
194 Formations in an ascending order (BGMRX, 1993). The bottoms of the Shawan, Taxihe,
195 Dushanzi, and Xiyu Formations in our seismic profile across the basin were dated at ~23.6 Ma,
196 ~20.1 Ma, ~16 Ma, and ~4.7 Ma, respectively, by correlating the seismic reflectors with the
197 magnetostratigraphic results in the northern Tian Shan (Fig. 4) (Charreau et al., 2005; Charreau
198 et al., 2009; Lu et al., 2010; Wang et al., 2013).

199 **3 Data**

200 The basic data for reconstructing the migration and subsidence history in the SJFB and
201 NTFB were derived from a ~141 km-long and 4-s-deep N-S trending seismic profile AA' across
202 the SJFB and a ~353 km-long and 6-s-deep seismic profile BB' across the NTFB extending from
203 the center of the Tarim basin to the Kuqa city (Figs. 1 and 5). The dominant frequency of the
204 seismic data is 28 Hz, and theoretical vertical seismic resolution or one-quarter wavelength for
205 the 28 Hz wavelet is ~18 ms (<45 m) in travel time. These profiles are parallel to the direction of

206 the convergence between the Tarim and Junggar blocks indicated by GPS measurements (Wang
207 and Shen, 2020; Wu et al., 2023). Based on well logging data near this profile, we converted the
208 two seismic time profiles into depth profiles. Considering the bending nature of the seismic
209 profile BB', we projected it onto a straight-line transverse to the NTFB axis so that it could be
210 used in our 2-D elastic plate subsidence model (Figs. 1 and 5).

211 The stratigraphic thicknesses used in back stripping calculations are derived from the
212 converted depth profiles of seismic profiles AA' and BB' (Fig. 5b-d). The decompaction
213 parameters used in the calculation are derived from Sclater and Christie (1980) (Table 1); while
214 the lithology, density, and top and bottom depths of each layer are obtained from profiles and
215 well logging data. We ignored eustatic sea-level changes because the epicontinental sea only
216 reached the western margins of the Tarim and Junggar basins in the Paleogene, and eventually
217 became isolated from the basins in the late Eocene (Bosboom et al., 2011; Li et al., 2018). The
218 paleobathymetry is estimated using sedimentary environment analyses of each stratigraphic unit
219 (e.g., Guo et al., 2002; Li et al., 2004; Shao et al., 2006; Bian et al., 2010; Yang et al., 2013), and
220 incorporates broad error bars.

221 The main parameters of the elastic plate model, for modelling the evolution of subsidence in
222 the NTFB and SJFB and the growth of the Tian Shan, include the density, width, surface slope
223 angle α , basal decollement dip angle β of the southern and northern Tian Shan thrust wedges, as
224 well as the effective elastic thickness T_e , Poisson's ratio ν , Young's modulus E of the Tarim and
225 Junggar lithospheres, and density of the asthenosphere mantle ρ_m (Fig. 6). The α and the present-
226 day width of the thrust wedges are obtained from an 80 km wide swath topographic profile
227 across the middle segment of the Tian Shan (Fig. 1c), where the α of the northern Tian Shan
228 wedge is $\sim 2.4^\circ$ and that of the southern Tian Shan is $\sim 1.5^\circ$. In our model, the parameters, ν

229 (0.25), E (5×10^{10} Pa), ρ_m (3300 kg m^{-3}), and gravity acceleration g (9.81 m s^{-2}) were set to
230 standard values (Aitken, 2011). Since the southern and northern Tian Shan thrust wedges are
231 mainly composed of Proterozoic–Paleozoic magmatic or metamorphic rocks (Xiao et al., 2013),
232 the average density of the thrust wedges in our model is set to the standard value for ancient
233 thrust wedge density (2800 kg/m^3) (Saura et al., 2015).

234 The wide-angle seismic reflection/refraction profiling across the Tian Shan from Karamay to
235 Kuqa reveals the complex decoupling architecture of the lower and middle crust and lithospheric
236 mantle of the Tarim and Junggar blocks beneath the junctions of the two basins and the Tian
237 Shan, which alters the crustal thickness of the Tarim and Junggar blocks (Zhao et al., 2003).
238 Therefore, although the shear wave velocity model of the crust and upper mantle of the Tian
239 Shan shows the dip angle of the Moho surface beneath the basin-mountain junctions (Lü et al.,
240 2019), the dip angle of the Moho cannot constrain the β of the southern and northern Tian Shan
241 wedges. We determined the values of β of the thrust wedges in our model according to the
242 geometry of the wedge coupled with the present-day tectonic subsidence profiles across the
243 basins in modelling results.

244 **4 Methods**

245 **4.1 Quantifying the migration of the Southern Junggar foreland basin**

246 We tracked all the seismic reflectors in profile AA' and identified northward onlap points of
247 the foreland sequence in the SJFB based on the northern termination sites of the reflectors. The
248 termination of a seismic reflector to the foreland (stratal onlaps in the foreland basin) represents
249 the distal end of deposition at that time. Generally, the thinnest sedimentary sequences or no
250 sediments occur in the forebulge of a foreland basin system, and thicken to the foredeep
251 (DeCelles & Giles, 1996). Accordingly, the envelope line of the distribution area of

252 forelandward reflector terminations denotes the boundary between the foredeep and the
253 forebulge (Li et al., 2019; Wang et al., 2020). Thus, the migration of the boundary relative to the
254 underlying plate can reflect that of a foreland basin (Fig. 6). Wang et al. (2013) divided the
255 sedimentary sequences in the SJFB into four tectonostratigraphic units according to the
256 unconformities between them. The upper-most unit is the Miocene-Quaternary foreland basin
257 unit which is associated with the late Cenozoic uplift of the Tian Shan. We tracked all the
258 seismic reflectors and determined the positions of their terminations in the Miocene-Quaternary
259 foreland basin unit imaged by profile AA'. The envelope line of the terminations of reflectors in
260 this foreland unit represents the trace of the southward migration of the forebulge of the SJFB.

261 Recent magnetostratigraphic studies of the Cenozoic strata in the northern Tian Shan provide
262 a chronostratigraphic framework (Fig. 4). The detailed ages of the Cenozoic strata were
263 correlated with profile AA' and extrapolated across the SJFB through a crossing seismic profile
264 (Wang et al., 2013). The ages of the seismic reflectors in the foreland basin were interpolated by
265 an assumption that the sedimentation rate between any two reflectors is constant. According to
266 the ages of seismic reflectors and distances between reflectors' terminations and the northern
267 Tian Shan wedge, the linear-regression of the onlap points on the envelope line yields a
268 migration rate of the forebulge in the SJFB relative to its basement.

269 **4.2 Modelling subsidence evolution of the NTFB and SJFB**

270 **4.2.1 Back stripping**

271 To model subsidence in the NTFB and SJFB, we applied a 2-D elastic rheology plate
272 model. Most flexural basins' observed basement subsidence profiles can be roughly predicted by
273 the 2-D elastic plate model in first-order (e.g., Yang and Liu, 2002; Saura et al., 2015). The

274 observed tectonic subsidence profiles across the basins from back stripping are the constraints
275 for modelling the evolution of subsidence of the NTFB and SJFB.

276 We divided the Cenozoic strata in the foredeep of the NTFB into three units using the
277 continuous seismic reflectors that correspond to the bottoms of the Kangcun (~13.4 Ma) and
278 Kuqa Formations (~5.3 Ma) in profile BB' (Fig. 5). Back stripping these units, we obtained the
279 observed tectonic subsidence profiles across the NTFB at ~13 Ma, ~5 Ma, and the present. The
280 Cenozoic strata in the SJFB are divided into four units using the continuous reflectors that
281 correspond to the bottoms of the Taxihe (~20.1 Ma), Dushanzi (~16.0 Ma) and Xiyu Formations
282 (~4.7 Ma) in profile AA' (Fig. 5). Back stripping these units yielded observed tectonic
283 subsidence profiles across the SJFB at ~20 Ma, ~16 Ma, ~5 Ma, and the present. The procedure
284 of back stripping includes decompaction, paleobathymetric correction, and flexural isostatic
285 stripping for calculating the tectonic subsidence (Allen and Allen, 2013). This methodology
286 requires some basic information including the lithology, top and bottom depths, age,
287 decompaction parameters (Table 1) and the paleo-water depth of each stratigraphic unit.

288 According to Li et al. (2020), the sediment drape created by the Tarim Basin's base level rise
289 since the Oligocene was not related to the tectonic load of the Tian Shan. Hence, we separated
290 the sediment drape from the tectonic subsidence before the flexural back stripping. The
291 calculation by Li et al. (2020) was used to determine the thickness of the sediment drape in this
292 procedure.

293 4.2.2 Numerical model

294 The tectonic load of the thrust wedge is imposed onto a semi-infinite elastic plate floating on
295 the asthenosphere in the model. We employ the finite difference solution for the flexure equation
296 based on a Python script called 'Gflex' (Wickert, 2016). Given that the critical angle of thrust

297 wedges tends to remain stable over millions of years (Davis et al., 1983), and no research has
298 documented changes in the critical angle of the Tian Shan, we reduced the tectonic loads of the
299 northern and southern Tian Shan thrust wedges to a triangular wedge imposed on the end of the
300 plate with a fixed critical wedge angle ($\alpha+\beta$ in Fig. 6).

301 Main parameters in the elastic plate model contain the Te , E , ν , ρ_c , ρ_m , g of the Tarim and
302 Junggar blocks, and the wedge angle (α , β), density (ρ_o) and width (W) of the thrust wedges of
303 the Tian Shan. For the modern NTFB and SJFB (0 Ma), the Te and β are only two unknown
304 variables in our modelling while the other parameters are known. The optimal values for these
305 two parameters are determined by minimizing the misfit between the observed and modelled
306 subsidence profiles across the Tarim Basin. There are certain trade-offs between the Te and β .
307 We apply the downhill simplex algorithm (Wright, 1996) to determine the best combination of
308 these two variables, and utilize Python's `scipy fmin` function to implement the downhill simplex
309 algorithm. We model the best combination of the Te of the modern Tarim and Junggar blocks
310 and the β of the modern thrust wedges using the trial-error method carrying out through a Python
311 program based on the 'Gflex' and the 'fmin.' For the historic NTFB and SJFB (~20 Ma, ~13–16
312 Ma, ~5 Ma), the historic Te and W are treated as variables in our modelling. We model the best
313 combination of the historic Te of the Tarim and Junggar blocks and the historic W of the thrust
314 wedges also using the trial-error method as described above.

315 The optimal values of W in the modelling results at ~20 Ma, ~13–16 Ma, ~5 Ma, and the
316 present-day indicate the variations in the W of the southern and northern Tian Shan thrust
317 wedges. Based on the variations in the W (P in Fig. 6), we calculated the propagation rates of the
318 southern and northern Tian Shan wedges (V_P in Fig. 3) in the direction perpendicular to the trend
319 of the range.

320 We also took into account how the modelling outcomes could be affected by the horizontal
321 convergence distance between the mountain wedge and the foreland basin basement (C in Fig.
322 6). Taking the SJFB as an example, we use the first end-member model with a minimum (zero)
323 horizontal convergence distance ($C = 0$), which represents a retro-foreland basin system, to
324 model the observed subsidence profiles at 0 Ma, ~4.7 Ma, ~16.0 Ma, and ~20.1 Ma. In this case,
325 the distance between the tectonic subsidence profiles from profile AA' at each time point and the
326 backstop of the northern Tian Shan wedge, the horizontal axis zero point, is the same. In other
327 words, the observed basin subsidence profiles at ~4.7 Ma, ~16.0 Ma, and ~20.1 Ma are at the
328 theoretical minimum distance from the thrust wedge. Based on the flexural isostasy, the required
329 tectonic load to cause the same amount of subsidence is proportional to the distance between the
330 load and the subsidence point (Turcotte and Schubert, 2002). The closer the distance, the lesser
331 the tectonic load required to induce the same amount of subsidence. Therefore, the predicted
332 tectonic loads of the northern Tian Shan wedges at ~4.7 Ma, ~16.0 Ma, and ~20.1 Ma in this
333 end-member model are at the theoretical minimum, representing the minimum of their width (W)
334 and the maximum of the propagation distance of the wedge (P) (Figs. 3 and 6).

335 For the second end-member model, we model the observed subsidence profiles at 0 Ma, ~4.7
336 Ma, ~16.0 Ma, and ~20.1 Ma by using the maximum horizontal convergence distance that is
337 equal to the migration distance of the foreland basin ($C = O$ in Fig. 6), which represents a pro-
338 foreland basin-thrust wedge system in a steady state (Naylor and Sinclair, 2008). In this case, the
339 observed tectonic subsidence profiles at ~4.7 Ma, ~16.0 Ma, and ~20.1 Ma were restored to a
340 pre-convergence position at a distance of the C from the top of the modern thrust wedge top.
341 Based on the elastic flexure, the predicted tectonic loads of the northern Tian Shan wedges at
342 ~4.7 Ma, ~16.0 Ma, and ~20.1 Ma in this end-member model are at the theoretical maximum

343 because we used the maximum horizontal convergence distance, reflecting the maximum of their
344 width (W) and the minimum propagation distance of the wedge (P). Hence, the maximum and
345 minimum values of the propagation distance of the southern and northern Tian Shan wedges (P),
346 as well as the range of their propagation rate V_P , were determined by our modelling using two
347 end members.

348 The results derived from the two end-member models constrain the ranges of the P and C in
349 the NTFB and SJFB systems. Combining the stratigraphic age framework, we calculate the
350 ranges of the propagation (V_P) and convergence (V_C) rates of the southern and northern Tian
351 Shan thrust wedges.

352 **5 Analyzing migration rate of the foreland basins**

353 The profile AA' depicts the structures and strata thickness variations in the SJFB (Fig. 7).
354 The fault-related folds of the northern Tian Shan fold-thrust belt form the southern part of the
355 profile, with the foredeep to the north. There is a thrust in the fold-thrust belt that occurs within a
356 Jurassic coal bed and has two arrays of growth anticlines in its hanging wall (Fig. 7; Wang et al.,
357 2013). The foredeep sedimentary layers comprise late Paleozoic-Cenozoic strata. The Shawan,
358 Taxihe, Dushanzi and Xiyu Formations in the upper part of the profile constitute the Miocene-
359 Quaternary foreland sedimentary layer, which is associated with the growth of the Tian Shan
360 (Fig. 7; Wang et al., 2013).

361 We tracked 64 reflectors in the foreland sedimentary layer, which were named R1 through
362 R64 in an ascending order (Figs. 7 and S1; Table S2 in the Supplementary material). Reflectors
363 R1 to R64 extend or terminate northwards within the seismic profile. There are 17, 11, 21, and
364 15 reflectors in the Shawan, Taxihe, Dushanzi and Xiyu Formations, respectively. Reflectors
365 R1–R30 in the Shawan, Taxihe Formations, and the lower part of the Dushanzi Formation are

366 well imaged and may thus be tracked credibly (Fig. 7). These reflectors are characterized by
367 sequential northward onlaps. We determined the positions of their northward terminations that
368 reflect the northward migration of onlapping points in these formations (Table S2). From R1 to
369 R29, the termination points expand northwards for ~93 km. The profile does not image R31–R64
370 in the upper Dushanzi Formation and the Xiyu Formation completely, therefore their seismic
371 nature and terminations cannot be determined. As a result, the migration of the onlap sites in the
372 Dushanzi and Xiyu Formations was not calculated.

373 Although terminations of seismic reflectors go back and forth with time (Figs. 7 and S1),
374 they migrate to the foreland overall. As described in section 4.1, the envelope of the distribution
375 area of forelandward reflector terminations indicates the migration of the foreland basin (Fig. 6).
376 To quantify the migration of the SJFB, we plotted the ages of strata represented by reflectors
377 versus the distances between reflector terminations and the northern Tian Shan wedge (the
378 boundary between the fold-thrust belt and the foredeep in Fig. 7). According to the ages of
379 seismic reflectors and their termination positions, the linear-regression analysis suggests that the
380 northward onlaps in the foreland sequence of the SJFB migrated at a rate of 44.6 ± 3.1 mm/yr
381 along 85°E from ~23 Ma to ~22 Ma (R1–R9), and migrated at a rate of 3.1 ± 0.2 mm/yr from
382 ~22 to ~16 Ma (R9–29) (see details of onlap rate uncertainty calculation in the Supporting
383 Information S1) (Fig. 8). The migration rate of the onlap points from ~23 to ~22 Ma even
384 outpaces the convergence rate (~40 mm/yr) between the Indian and Eurasian plates during the
385 same period based on paleomagnetic records (Guillot et al., 2003; Copley et al., 2010). Hence,
386 the onlaps from ~23 to ~22 Ma (R1–R9) may reflect the initial filling process of the foreland
387 basin rather than the forebulge's migration within the basin driven by the convergence between
388 the Junggar block and the northern Tian Shan. The migration rate of the northward onlaps in

389 foreland sequences from ~22 to ~16 Ma should reflect the northward migration rate V_o (Fig. 3)
390 of the SJFB relative to the wedge top of the northern Tian Shan (Wang et al., 2013; Li et al.,
391 2022).

392 Li et al. (2019) applied the method described above to identify the onlap points in the
393 Cenozoic foreland basin unit imaged by profile BB' across the NTFB and calculated the
394 migration rates of the foreland basin (V_o in Fig. 3) based on magnetostratigraphic constraints.
395 The forebulge of the NTFB migrated southward at a rate of 1.6 ± 0.1 mm/yr between ~26 and
396 ~12 Ma, and at a rate of 14.6 ± 0.1 mm/yr after ~12 Ma.

397 **6. Modelling results**

398 **6.1 The Northern Tarim foreland basin**

399 By back stripping the foreland strata in the profile BB', we obtained the tectonic subsidence
400 profiles across the NTFB at ~13.4 Ma, ~5.3 Ma, and the present day (Fig. 5). We used the first
401 end-member model without horizontal convergence ($C = 0$) to model the observed subsidence
402 profiles, and the results reflect the maximum value of the P of the southern Tian Shan wedge
403 (Fig. 9a–c).

404 The width of the southern Tian Shan thrust wedge is a known value when modelling the
405 observed a tectonic subsidence profile at 0 Ma, whereas its β is a variable. The swath
406 topographic profile indicates that the width of the thrust wedge is ~92 km (Fig. 1). The
407 modelling results demonstrate that the best fit between the observed and predicted subsidence
408 profile is achieved with the optimal value of the T_e of ~61 km and the β of the southern Tian
409 Shan thrust wedge of ~7.8°.

410 The optimal width of the southern Tian Shan thrust wedge has increased from ~53 km to ~71
411 km from ~13.4 Ma to ~5.3 Ma with an average propagation rate of ~2.2 mm/yr, and increased

412 from ~71 km to ~92 km since ~5.3 Ma with an average propagation rate of ~4.4 mm/yr, based on
413 modelling results of the observed subsidence profile at ~13.4 Ma and ~5.3 Ma. The modelling
414 results also reveal that the optimal value of the Te of the Tarim block has gradually increased
415 from ~58 km to ~61 km from ~13.4 Ma to the present.

416 Using the second end-member model with a theoretical maximum value of the horizontal
417 convergence between the thrust wedge and basin basement, the minimum value of propagation
418 (P) of the southern Tian Shan thrust wedge are predicted by modelling the observed subsidence
419 profiles across the NTFB (Fig. 10a–c).

420 The same results were obtained in this modelling because the modelling parameters at 0 Ma
421 were the same as those of the first end-member model with no horizontal convergence.

422 When modelling the observed subsidence profiles at ~13.4 Ma and ~5.3 Ma, the horizontal
423 convergence distance (C in the model) between the Tarim block and the southern Tian Shan
424 wedge, was set at ~137 km and ~54 km, respectively, for the profiles at ~13.4 Ma and ~5.3 Ma
425 according to the migration distance of the NTFB (O), as determined by seismic profiles analysis
426 (Li et al., 2019). To restore the observed subsidence profiles at ~13.4 Ma and ~5.3 Ma to their
427 pre-convergence positions, they were moved southward by ~137 km and ~54 km, respectively.
428 According to the modelling, the predicted width of the southern Tian Shan wedge has remained
429 constant at ~92 km since ~13.4 Ma, indicating a theoretical minimum propagation rate of zero.
430 The modelling also revealed that the optimal value of Te was ~90 km at ~13.4 Ma and has
431 decreased to 61 km.

432 **6.2 The Southern Junggar foreland basin**

433 We obtained the tectonic subsidence profiles across the SJFB at ~20.1 Ma, ~16.0 Ma, ~4.7
434 Ma, and the present day by back stripping the foreland strata in the profile AA' (Fig. 5). We used

435 the first end-member model with no horizontal convergence to model the observed subsidence
436 profiles, and the outcomes reflected the maximum value of propagation of the northern Tian
437 Shan wedge (P) (Fig. 9d–g).

438 When modelling the observed tectonic subsidence profile at 0 Ma, the width of the northern
439 Tian Shan wedge is a known value, while its β is variable. According to the swath topographic
440 profile, the thrust wedge is ~71 km wide (Fig. 1). The modelling results show that a T_e of 35 km
441 and β of 7.0° for the northern Tian Shan wedge are optimal for achieving the best fit between the
442 observed and predicted subsidence profile.

443 The modelling results of the observed subsidence profiles at ~20.1 Ma, ~16.0 Ma, and ~4.7
444 Ma indicate that the width of the northern Tian Shan wedge has increased from ~42 km to ~53
445 km during 20.1–16.0 Ma with an average propagation rate of ~2.6 mm/yr, from ~53 km to ~62
446 km during 16.0–4.7 Ma with an average rate of ~0.8 mm/yr, and from ~62 km to ~71 km since
447 ~4.7 Ma with a rate of ~1.9 mm/yr. The modelling results also show that from ~20.1 Ma to the
448 present, the optimal value of the T_e of the Junggar block has gradually increased from ~33 km to
449 ~35 km.

450 Using the second end-member model with a theoretical maximum value of the horizontal
451 convergence between the thrust wedge and basin basement, the minimum value of propagation
452 (P) of the northern Tian Shan wedge is predicted by modelling the observed subsidence profiles
453 across the SJFB, (Fig. 10d–g).

454 The modelling conditions at present were identical to those of the first end-member model
455 with no horizontal convergence, yielding the same results.

456 The value of the convergence distance (C) was set at ~19 km, ~7 km, and ~3 km when
457 modelling the observed subsidence profiles at ~20.1 Ma, ~16.0 Ma, and ~4.7 Ma, respectively,

458 according to the migration distance of the SJFB obtained by analyzing seismic profiles (Li et al.,
459 2022). The observed subsidence profiles at ~20.1 Ma, ~16.0 Ma and ~4.7 Ma were moved
460 northward by ~19 km, ~7 km and ~3 km, respectively, to restore them to their pre-convergence
461 positions. According to the modelling, the northern Tian Shan wedge's predicted width increased
462 from ~49 km to ~58 km during 20.1–16.0 Ma with an average propagation rate of ~2.2 mm/yr,
463 from ~58 km to ~66 km during 16.0–4.7 Ma with an average rate of ~0.7 mm/yr, and from ~66
464 km to ~71 km from ~4.7 Ma to the present with an average rate of ~1.1 mm/yr. The modelling
465 also showed that the T_e was at its ideal value of ~42 km at ~20.1 Ma and then reduced to the
466 present-day ~35 km.

467 **6.3 The convergence rate**

468 The range of the horizontal convergence rates between the Tarim block and the Tian Shan
469 are constrained according to the propagation rates of the southern Tian Shan thrust wedge
470 (derived from the modelling results) and the range of the onlap rates of the foreland sequence
471 within the NTFB (Fig. 11 and Table 2). The modelling results show a range of the propagation
472 rates of 0–2.2 mm/yr for the southern Tian Shan thrust wedge during 13.4–12.0 Ma, with a
473 maximum value exceeding the observed onlap rate of foreland sequences (~1.6 mm/yr) during
474 the same time period. This yields a horizontal convergence rate range of 0–1.6 mm/yr. From
475 ~12.0 Ma to ~5.3 Ma, the range of predicted propagation rates of the wedge was 0–2.2 mm/yr,
476 and the onlap rate of the foreland sequence strata was ~14.6 mm/yr (Li et al., 2019), resulting in
477 a horizontal convergence rate range of 12.4–14.6 mm/yr. From ~5.3 Ma to ~1.7 Ma, the range of
478 predicted propagation rates of the wedge was 0–4.38 mm/yr, the onlap rate was ~14.6 mm/yr,
479 leading to a horizontal convergence rate range of 10.2–14.6 mm/yr.

480 Based on the predicted propagation rates of the northern Tian Shan wedge and the onlap rates
481 of the foreland sequences in the SJFB, we calculated the range of the horizontal convergence
482 rates between the Junggar block and the northern Tian Shan (Fig. 11). From ~20.1 Ma to ~16.0
483 Ma, the range of horizontal convergence rates was 0.5–0.9 mm/yr according to the onlap rate of
484 ~3.1 mm/yr and the range of predicted propagation rate of the northern Tian Shan of 2.2–2.6
485 mm/yr. From ~16.0 Ma to ~4.7 Ma, the range of the predicted propagation rates was 0.7–0.8
486 mm/yr, but the onlap rates of the foreland sequence in the SJFB are unknown during this period
487 because the Dushanzi and Xiyu Formations are not entirely imaged in the profile AA'. Another
488 seismic profile located ~40 km west of profile AA' shows that the conglomerate-sandstone
489 transition in the basin-fill of the SJFB migrated northward at a rate of 0.4 ± 0.1 mm/yr from ~23
490 Ma to ~6 Ma along the longitude of 84°E. The forelandward migration rate of the conglomerate-
491 sandstone transition in foreland basins is thought to be similar to the forelandward onlap rate of
492 the basins (e.g., Burbank et al., 1988; Schlunegger & Norton, 2015; Dingle et al., 2016). The
493 migration rate (0.4 ± 0.1 mm/yr) of the conglomerate-sandstone transition in the SJFB is lower
494 than the predicted propagation rate (0.7–0.8 mm/yr) of the northern Tian Shan wedge from ~16.0
495 Ma to ~4.7 Ma. Considering that the lateral variation within 40 km has little effect on migration
496 rate magnitude, the horizontal convergence rate between the Junggar block and the northern Tian
497 Shan is close to zero during this period.

498 **6.4 Tectonic subsidence rate**

499 We obtained the changes in the tectonic subsidence rates in the NTFB and SJFB since the
500 Neogene, corrected for sediment loading by back stripping for the seven wells in these two
501 basins. Wells 4, 5, 6, and 7 are located in the NTFB, with Well 4 being in the center of the
502 foredeep and Well 7 being in the proximal foredeep (Figs. 1 and 4).

503 The tectonic subsidence curves from these four wells show the maximum tectonic subsidence
504 in the NTFB at ~3.5 km, and the convex-upward patterns of accelerating subsidence rates from
505 ~26 Ma to the present (Table 3; Fig. 12), in accordance with the tectonic subsidence trend in
506 typical pro-foreland basins (DeCelles and Giles, 1996; Naylor and Sinclair, 2008; Sinclair and
507 Naylor, 2012). Wells 8, 9, and 10 are located in the SJFB, with Well 10 being in the distal
508 foredeep and Well 8 being in the proximal foredeep. The subsidence curves from these three
509 wells show that the maximum tectonic subsidence in the basin is ~1.2 km, with a tectonic
510 subsidence rate faster than that of the NTFB from ~20 Ma to ~16 Ma. The subsidence rate
511 rapidly decreased from ~12 Ma to ~5 Ma and was lower than that of the NTFB. Since ~5 Ma, the
512 tectonic subsidence of these three wells has accelerated again, but the subsidence rate was still
513 lower than that of the NTFB. These tectonic subsidence curves show a tectonic subsidence trend
514 non-conforming to the characters of pro- or retro-foreland basins (Table 3; Fig. 12).

515 **7 Discussion**

516 The forelandward migration rates and subsidence history of the NTFB and SJFB are derived
517 from the seismic profiles across these basins. Based on the migration rates and observed
518 subsidence profiles, we used an elastic numerical model to describe the evolution of tectonic
519 subsidence in the foreland basins combined with the formation of the southern and northern Tian
520 Shan wedges. The modelling results reveal the evolution of the tectonic load and propagation
521 rates of the southern and northern Tian Shan.

522 **7.1 Deep lithospheric architecture beneath the Tian Shan unveiled by its bilateral foreland** 523 **basins**

524 The relationship between the foreland sequences onlap rates in the NTFB and SJFB and the
525 propagation rates of the southern and northern Tian Shan thrust wedges show the plate setting

526 characteristics of these two basins since ~20 Ma according to the foreland basin-thrust wedge
527 theories (Johnson and Beaumont 1995; Sinclair, 2005; Naylor and Sinclair, 2008). The data
528 suggests a two-stage evolution of the deep lithospheric architecture of the middle segment of the
529 Tian Shan (Fig. 13).

530 From the early to middle Miocene, the Tian Shan region experienced the first stage of
531 lithospheric evolution. On the northern side of the Tian Shan, the onlap rate of the foreland
532 sequence in the SJFB depicted by profile AA', ~3.1 mm/yr (V_{O-J} in Fig. 13a) during ~20–16 Ma,
533 was larger than the predicted propagation rate of the northern Tian Shan wedge, 2.2–2.6 mm/yr
534 (V_{P-J} in Fig. 13a) (Fig. 11 and Table 2). This is consistent with the characteristic of a pro-
535 foreland basin where stratal onlaps onto the basin basement toward the foreland have a rate
536 higher than the propagation rate of the coupled thrust wedge (Fig. 3) (Johnson and Beaumont
537 1995; Naylor and Sinclair, 2008). Hence, the SJFB is characteristic of the plate setting of a pro-
538 foreland basin. On the southern side of the Tian Shan, the time equivalent onlap rate of the
539 foreland sequence in the NTFB is ~1.6 mm/yr (V_{O-T} in Fig. 13a), which is only approximately
540 half that of the SJFB. Low-temperature thermochronological studies and balanced section
541 analyses reveal that the southern Tian Shan thrust wedge experienced at least one phase of rapid
542 uplift, exhumation and shortening event during 20–16 Ma (Hubert-Ferrari et al., 2007; Yu et al.,
543 2014; Chang et al., 2017a). This indicates that the southern Tian Shan wedge began to propagate
544 during this stage (Dumitru et al., 2001; Du et al., 2007). Its propagation rate (V_{P-T} in Fig. 13a)
545 could be on the same order of magnitude as that of the northern Tian Shan wedge (2.2–2.6
546 mm/yr), as indicated by the estimate of balanced sections in the southern Tian Shan fold-thrust
547 belt (Li et al., 2023), and the sandbox modelling (Sun et al., 2022a) and numerical modelling
548 (Naylor and Sinclair, 2007) of doubly vergent orogeny. Therefore, the stratigraphic onlap in the

549 NTFB at a low rate of, ~ 1.6 mm/yr (V_{O-T} in Fig. 13a), should be dominantly induced by the
550 southward propagation of the southern Tian Shan wedge (V_{P-T} in Fig. 13a) in this period. This
551 reflects that the NTFB is characteristic of the plate setting of a retro-foreland basin. In addition,
552 the tectonic subsidence rate of the SJFB during this stage is faster than that of the NTFB (Fig.
553 12), confirming the prediction that pro-foreland basins have rapid and accelerating subsidence,
554 whereas retro-foreland basins have slowing subsidence (Sinclair and Naylor, 2012). Therefore,
555 the observation that the NTFB on southern side of the Tian Shan was characteristic of a retro-
556 foreland basin, while the SJFB on the counterpart conformed to the characteristics of a pro-
557 foreland basin, is consistent with the predictions of the Tian Shan's unidirectional underthrusting
558 model (Fig. 13a). This implies that the Tarim Block beneath the retro-foreland basin likely acted
559 as an overriding plate in this stage, while the Junggar Block beneath the pro-foreland basin as an
560 underthrusting plate, according to the foreland basin-thrust wedge theories (Sinclair, 2005;
561 Naylor and Sinclair, 2008; Sinclair and Naylor, 2012).

562 The ongoing India-Eurasia collision revitalized the Paleozoic Tian Shan orogen (Tapponnier
563 et al., 1982; Dayem et al., 2009), meaning that the Tarim block (northward moving) was the
564 'active block' and the Junggar block was the 'passive block' during their convergence.

565 Lithosphere indentation and mantle subduction are two main drivers that can create and sustain
566 intraplate orogenesis (Ellis, 1996; Sun et al., 2022a). Given that the plate settings of the NTFB
567 and SJFB reveal the Junggar block as the underthrusting lithosphere and the Tarim block as the
568 overriding lithosphere during this period, we hypothesize that the Tarim block recessed into the
569 Tian Shan, acting as an 'indenter' to generate Tian Shan uplift (Fig. 13a). This is analogous to
570 the late Cenozoic intra-continental orogeny of the Qilian Shan on the northern margin of the
571 Tibetan Plateau, which was driven by lithospheric indentation-mode convergence between the

572 Qaidam block and the North China craton (Zuza et al., 2016; Sun et al., 2022a). The passive
573 underthrusting of the Junggar block beneath the Tian Shan during this stage could also be the
574 reactivation of the Paleozoic southward subduction structures of the Junggar block beneath the
575 northern Tian Shan, which was inherited from the late Paleozoic collision of blocks in the region
576 (Charvet et al., 2011; Xiao et al., 2013).

577 During 16–12 Ma, the predicted propagation rate of the northern Tian Shan wedge from the
578 modelling results decreased to 0.7–0.8 mm/yr but exceeded the migration rate (0.4 ± 0.1 mm/yr)
579 of the conglomerate-sandstone transition in the basin-fill of the SJFB imaged by seismic
580 profiling, which is considered to be close to the forelandward onlap rate of the basins (e.g.,
581 Dingle et al., 2016; Li et al., 2022). This implies that the foreland onlap rate of the SJFB during
582 16–12 Ma could not have been higher than the propagation rate of the northern Tian Shan. When
583 combined with the observation that the tectonic subsidence rate in the SJFB slowed down
584 significantly between 16–12 Ma (Fig. 12), the SJFB may have become characteristic of a retro-
585 foreland basin during this period, rather than those of a pro-foreland basin (Naylor and Sinclair,
586 2008). This suggests that the underthrusting of the Junggar block may have stalled. The
587 stratigraphic onlap rate (~ 1.6 mm/yr) in the NTFB during 16–12 Ma, is likewise smaller than the
588 maximum predicted propagation rate of the southern Tian Shan wedge, of ~ 2.2 mm/yr.
589 Consequently, the NTFB is still characteristic of the plate setting of a retro-foreland basin
590 between ~ 16 Ma and ~ 12 Ma.

591 From the late Miocene until the present, the Tian Shan region experienced the second stage
592 of lithospheric evolution. During this time, the stratigraphic onlap rate in the NTFB (V_{O-T} in Fig.
593 13b) of ~ 14.6 mm/yr substantially exceeded the predicted propagation rate of the southern Tian
594 Shan wedge of ~ 2.2 mm/yr from ~ 12 Ma to ~ 5 Ma, and the rate of ~ 4.4 mm/yr from ~ 5 Ma to

595 the present (Fig. 11; Table 2). Additionally, the tectonic subsidence of the Tarim Basin
596 accelerated significantly during this period, exceeding the subsidence rate of the SJFB (Fig. 12;
597 Table 3). Our findings suggest that the Tarim Basin evolved into the plate setting of a pro-
598 foreland basin, aligning with the typical features associated with pro-foreland basins (Fig. 3).
599 This implies that the Tarim Block formed the underthrusting lithosphere beneath the Tian Shan
600 (Fig. 13b). The foreland onlap rate of the SJFB (V_{O-J} in Fig. 13b) during this period, as revealed
601 by the conglomerate-sandstone transition migration rate (Li et al., 2022), was still smaller than
602 the predicted propagation rate of the northern Tian Shan wedge (V_{P-J} in Fig. 13b), which ranged
603 from 0.4–1.9 mm/yr. Also, the tectonic subsidence rate in the SJFB decreased compared to
604 before ~16 Ma (Table 3), which is consistent with the tectonic subsidence trend in retro-foreland
605 basins. Therefore, the SJFB was characteristic of the plate configuration of a retro-foreland basin
606 during this period, suggesting that the Junggar block evolved into the overriding lithosphere
607 beneath the Tian Shan.

608 The change like the foreland basins on both sides of the Tian Shan after the middle Miocene
609 indicates a shift in the convergence pattern of the Tarim Block towards the Tian Shan, from
610 lithospheric indentation to lithospheric subduction (Fig. 13). The current unidirectional
611 underthrusting mountain-building model of the Tian Shan unveiled by the evolution of its
612 bilateral foreland basins is consistent with the deep architecture model in which the Tarim
613 block's lithosphere was subducted to mantle depths beneath the southern Tian Shan (Fig. 2), as
614 revealed by ambient noise tomography (Sun et al., 2022b). It is also in agreement with the results
615 of the wide-angle seismic reflection/refraction profiling from Karamay to Kuqa, which show that
616 the Moho of the Tarim block dips down to the north beneath the southern Tian Shan, while there

617 is a continuous and flat Moho beneath the junction of the northern Tian Shan and Junggar Basin
618 (Zhao et al., 2003; Gilligan et al., 2014).

619 The migration and subsidence history of the NTFB and SJFB indicate that the Tarim block
620 indented northward into the Tian Shan during the early to middle Miocene, triggering its uplift.
621 From the late Miocene to the present, the convergence pattern between the Tarim and Junggar
622 blocks changed from lithospheric indentation to subduction, with the Tarim block presently
623 subducting beneath the Tian Shan (Fig. 13b).

624 The tectonic regime of the Tibetan Plateau during this period may have influenced the
625 transformation of the deep architecture of the Tian Shan in the middle to late Miocene (Dayem et
626 al., 2009; Huangfu et al., 2021). The finite element numerical simulation reveals that the direct
627 contact and collision between the Indian and Tarim lithospheric mantles beneath western Tibet
628 occurred, ~30 Ma after the India-Eurasia initial collision, dominating the late Cenozoic mountain
629 building of the Tian Shan (Huangfu et al., 2021). The direct collision facilitated the compression
630 stress transmission over a large distance from the India plate to the Tian Shan (Calignano et al.,
631 2015; Huangfu et al., 2021) to cause rapid uplift of the mountain range since the middle Miocene
632 (e.g., Yu et al., 2014; Wang et al., 2023). Therefore, the increase in stress transmitted from the
633 Tarim block to the Tian Shan could be the main driver for the change of the convergence
634 patterns from lithosphere indentation to subduction. The restriction of the southward
635 underthrusting of the Junggar block after the middle Miocene might be a result of the re-locking
636 of the décollement structures between the Junggar block and the northern Tian Shan wedge, due
637 to the increased topographic load of the latter (Burov and Toussaint, 2007). Furthermore, due to
638 the encounter with deep high-density layers, the increasing resistance of the underthrusting
639 Junggar lithospheric mantle may also limit subsequent underthrusting (Capitanio et al., 2010). In

640 addition, during the Miocene epoch, the delamination and break-off of the Indian and Asian
641 lithospheres resulted in the outward growth of the Tibetan Plateau (Kapp & DeCelles, 2019),
642 which involved rapid surface uplift within northern Tibet, the Qilian and Kunlun Mountains
643 (e.g., Molnar and Stock, 2009; Ding et al., 2022), as well as the mid-crustal channel flow and
644 ductile extrusion of the Greater Himalaya (e.g., Mukherjee and Koyi, 2010; Mukherjee, 2013).
645 One hypothesis suggests that the increasing elevation of the Tibetan plateau during the Miocene
646 caused radially oriented compressive strain in the surrounding area, potentially influencing the
647 transformation of the deep architecture of the Tian Shan (Molnar and Stock, 2009).

648 Moreover, understanding the geodynamic context of the foreland basins in terms of it being a
649 retro- or pro-foreland basin aids hydrocarbon prospectivity in the basins (Bourrouilh et al., 1995;
650 Naylor and Sinclair, 2008; Allen and Allen, 2013). For example, the rapid subsidence of the
651 NTFB during the deposition of the Kuqa Formation resulted in the under-compaction, rapid
652 hydrocarbon generation and significant increase in the residual pressure within the source rock
653 formations in the Bozi-Dabei natural gas field within the basin (Yang et al., 2022; Wang et al.,
654 2022). This pressure difference between the source and reservoir provided the dynamic for the
655 migration of ultra-high-pressure natural gas into the reservoirs. The pro-foreland basin nature of
656 the NTFB, influenced by its plate setting, determined the rapid and accelerating subsidence trend
657 in the basin (Yang et al., 2022).

658 **7.2 Implications of modelling on topographic growth**

659 Our modelling of the subsidence process in the NTFB and SJFB predicts that the average
660 elevations of the southern Tian Shan were no less than ~58% and ~77% of their present height at
661 ~13.4 Ma and ~5.3 Ma, respectively; and the northern Tian Shan's average elevations were at
662 least ~56%, ~75%, and ~87% of their present height at ~20.1 Ma, ~16.0 Ma, and ~4.7 Ma,

663 respectively (Figs. 8 and 9). Considering that the Mesozoic Tian Shan was dominated by low-
664 relief and small hills localized along discrete tectonic structures (Morin et al., 2019; He et al.,
665 2021b), our modelling results suggest that average elevations of both the southern and northern
666 Tian Shan had started to rise before the Miocene and reached half of their current average
667 elevation by the middle Miocene. This is in agreement with the continuous cooling and
668 exhumation in the region from the Eocene to Quaternary (e.g., Dumitru et al., 2001; Yu et al.,
669 2014; Chang et al., 2021), which is indicated by the available apatite fission track and zircon and
670 apatite (U-Th)/He ages varying from ~50 Ma to ~3 Ma in the region (Fig. 14) assuming a
671 constant value of geothermal gradient in the Tian Shan during the Cenozoic (Wang et al., 2023).
672 Hence, the topographic uplift before the middle Miocene could have contributed to the modern
673 mountain building of the middle segment of the Tian Shan. Our modelling also predicts that the
674 propagation rates of the northern Tian Shan wedge decreased by ~60% from ~16 Ma to ~5 Ma
675 compared with ~20–16 Ma (Fig. 11; Table 2). Considering that the pro-wedge of Alpine-type
676 orogenic belt has a faster extension rate than the retro-wedge in the growth stage (Ellis, 1996;
677 Vogt et al., 2017), this could also suggest that northern Tian Shan has transformed from a pro-
678 wedge to a retro-wedge after the middle Miocene.

679 The predicted average propagation rate of the southern and northern Tian Shan wedge from
680 ~5 Ma to the present is roughly double that of the period between ~12 and ~5 Ma, reflecting the
681 accelerated the uplift of the Tian Shan since ~5 Ma. This is in agreement with the continuous
682 acceleration of slip rates on thrust faults of the fold-thrust belts and sedimentation rates in the
683 foreland basins on both sides of the Tian Shan since the Quaternary (e.g., Sun et al., 2004; Huang
684 et al., 2006; Charreau et al., 2009; Lu et al., 2019; Li et al., 2023). The predicted acceleration of
685 the topographic growth is also consistent with the imbalance between an influx of material

686 (crustal thickening) and erosional efflux in the modern Tian Shan, the former outpaced the latter
687 by a factor of ~ 10 (Charreau et al., 2023).

688 The southern Tian Shan thrust wedge has been propagating at an average pace of ~ 2.2 mm/yr
689 since ~ 5 Ma, which is about twice as fast as the northern Tian Shan wedge (Table 2). This
690 difference in propagation rates between the southern and northern Tian Shan wedges agrees with
691 the characteristics of the propagated pattern of pro- and retro-wedges (Ellis, 1996; Vogt et al.,
692 2017). GPS observations (Zubovich et al., 2010; Shen and Wang, 2020) and balanced section
693 studies (Hubert-Ferrari et al., 2007) reflect that the frontal fold-and-thrust belt on the southern
694 piedmont of the southern Tian Shan (the current pro-wedge) absorbs most of the crustal
695 shortening in the wedge, suggesting that the range growth of the southern Tian Shan appears to
696 have been essentially sustained by frontal accretion of material from the crust of the Tarim block.
697 On the contrary, the northern Tian Shan's range growth, as the retro-wedge, could primarily be
698 supported by the uplift of the hinterland (Sun et al., 2022a). The distribution of the cooling ages
699 obtained in the same swath profile across the middle segment of the Tian Shan supports this
700 difference in the range growth pattern between the southern and northern Tian Shan thrust
701 wedges (Fig. 14), because samples with late Cenozoic cooling ages in the southern Tian Shan
702 were mainly obtained from the frontal edge of the thrust wedge, whereas those from the northern
703 Tian Shan were mainly taken from the hinterland region (Fig. 14). This reflects that the majority
704 of exhumation events in the southern Tian Shan region occurred at the frontal area of the wedge
705 as a typical pro-wedge, while those of the northern Tian Shan main occurred in its hinterland due
706 to its retro-wedge-style (Sinclair et al., 2005). Considering that δO^{18} isotopes and palynology in
707 the Tian Shan show a stable arid climate with stable low erosion since the Oligocene (Sun et al.,
708 2007; Macaulay et al., 2016; Jepson et al., 2021), the distribution of exhumation events reveals

709 that the frontal area of the southern Tian Shan wedge exhibits more active crustal shortening and
710 uplift in comparison to its hinterland, whereas the reverse pattern is observed in the northern
711 Tian Shan. In addition, the distribution of the cooling ages shows a southward migration of the
712 strongest exhumation area in the southern Tian Shan towards the frontal of the wedge at ~12 Ma
713 (Fig. 14), which may be related to enhanced lateral propagation of the southern Tian Shan thrust
714 wedge as a result of transformation from a retro-wedge to a pro-wedge (Sun et al., 2022).

715 **7.3 Implications on crustal shortening rates**

716 The timing and velocity of crustal shortening absorbed by the Tian Shan can aid in
717 understanding how deformation propagated from the southern Asian margin to remote intra-
718 continental regions (Tapponnier et al., 1982, 2001; Neil and Houseman, 1997; Dayem et al.,
719 2009), and paleomagnetism reveals a broad range of the crustal shortening between Tarim and
720 Junggar lithospheres at 400 ± 600 km (Chen et al., 1992). Based on the stratigraphic onlap rates in
721 the NTFB and SJFB obtained from seismic profiles and the propagation rates of the southern and
722 northern Tian Shan thrust wedges obtained from modelling results, we calculated the horizontal
723 convergence rates between the Tarim and Junggar blocks since ~20 Ma, which represents the
724 crustal shortening rates absorbed by the middle segment of the Tian Shan.

725 The crustal shortening rate absorbed by the Tian Shan was less than 2 mm/yr between 20–12
726 Ma (Fig. 11; Table 2) according to our calculations, which is only ~4% of the total convergence
727 rate between the Indian and Eurasian continents during the same period (~50 mm/yr) as
728 reconstructed by paleomagnetic data (Guillot et al., 2003; Copley et al., 2010). The oldest
729 sedimentary sequence of the foreland succession in the NTFB was, deposited at ~26 Ma based
730 on magnetostratigraphic constraints (Charreau et al., 2006; 2009; Huang et al., 2006), indicating
731 that uplift of the modern Tian Shan was initiated no later than ~26 Ma (Li et al., 2019). Hence

732 the deformation caused by the India-Asia collision has already propagated to the Tian Shan by
733 the Oligocene. However, the majority of the crustal shortening during this period was absorbed
734 by the compressional and strike-slip structures in and around the Tibetan Plateau (Tapponnier et
735 al., 2001), leaving less than 4% of the total strain to be absorbed by the Tian Shan. The crustal
736 shortening rate of the Tian Shan increased to 10–14 mm/yr at ~12 Ma according to our
737 calculations, accounting for around 25–35% of the total convergence rate between the Indian and
738 Eurasian continents during the same period (~40 mm/yr) (Guillot et al., 2003; Copley et al.,
739 2010). Low-temperature thermochronological results from the Qilian Shan in the northeastern
740 margin of the Tibetan Plateau shows a similar fast tectonic uplift during the late Miocene (e.g.,
741 Zheng et al., 2010). These demonstrate that the intra-continental deformation brought on by the
742 India-Eurasia collision led to compressive strain which was radially orientated in the region
743 surrounding Tibet after the late Miocene (Molnar and Stock, 2009), and this region developed
744 into one of the most active tectonic zones. This kind of strain distribution mechanism tends to
745 transfer compressive stress to the areas in the northern Tibetan Plateau, (such as the Tian Shan),
746 and might also be related to the direct collision between the Indian lithospheric mantle and the
747 Tarim block (Huangfu et al., 2021), which resulted in strain concentration in the Tian Shan. The
748 range consequently absorbed a greater percentage of crustal shortening.

749 Furthermore, given the continuous Cenozoic sedimentary sequences observed in the foreland
750 basin systems on either side of the Qilian Shan orogen (Zuza et al., 2016), it is likely that our
751 research methods can be effectively employed to investigate the rates of crustal shortening and
752 the lithospheric architecture of the Qilian Shan in future studies.

753 **7.4 The optimal T_e and β values in numerical modelling results**

754 T_e is a key parameter in modelling lithospheric flexural deflection. In our model, the optimal
755 T_e values were determined by minimizing the misfits between the observed and predicted
756 subsidence profiles. The optimal value of T_e for the lithosphere of the modern Tarim and
757 Junggar blocks obtained in our modelling is consistent with the predictions derived from gravity
758 anomalies and geothermal data. The T_e value for the Tarim block is 53 km, which is quite near to
759 the median value of 66 ± 7 km as determined by the lithospheric thermo-rheological structure
760 (Liu et al., 2006). The predicted T_e value of 35 km for the Junggar block is slightly lower than
761 that (40–50 km) obtained from the flexural and rheological modelling based on Bouguer gravity
762 anomaly data (Jiang, 2014). Considering that our profile is located in the western segment of the
763 Junggar Basin, this difference does not contradict Jiang's (2014) prediction of a decreasing trend
764 of the T_e value of the Junggar block from the basin center to the west.

765 In the case of no horizontal convergence, the predicted optimal values of T_e for the Tarim
766 and Junggar blocks both increased over the late Cenozoic. Many factors that affect lithospheric
767 rheology (e.g., geothermal condition, lithospheric composition, and mechanical weakening) may
768 be expressed through the T_e (Burov and Diament, 1995). It is unclear why these lithosphere's T_e
769 values are rising, but the results are in line with the cooling process occurring in the Tarim and
770 Junggar Basins. The paleogeothermal gradients in the Tarim Basin decreased slowly from ~ 2.7
771 to ~ 2.2 °C/100 m during the Paleogene to ~ 2.1 °C/100 m at present (Wang et al., 1995; Liu et al.,
772 2006; Chang et al., 2017b), and the average heat flow of the Junggar Basin decreased from ~ 50
773 mW m^{-2} to ~ 42 mW m^{-2} from the Cretaceous to the present (Qiu et al., 2005). The T_e values are
774 sensitive to fluctuation in the heat flow when the average heat flow is between ~ 40 mW m^{-2} and
775 ~ 70 mW m^{-2} (Hyndman et al., 2009; He et al., 2017). Considering an average heat flow of

776 $\sim 44 \text{ mW m}^{-2}$ in the modern Tarim Basin (Hu et al., 2000; Liu et al., 2015), the cooling process
777 there may have been the primary factor contributing to the increase in the Te value. Moreover,
778 the optimal value of Te for the Tarim and Junggar blocks at ~ 20 Ma, ~ 13 Ma, and ~ 5 Ma is even
779 higher than the modern Te value in cases with maximum convergence distance, C . The decrease
780 in Te is contrary to the cooling process in the Tarim and Junggar Basin (Qiu et al., 2005; Liu et
781 al., 2006). These two predictions indicate that a larger convergence distance value leads to a
782 larger predicted optimal value of Te . Consequently, the main factor potentially responsible for
783 the abnormally high Te value is our possible overestimation of the convergence distance, C ,
784 since ~ 20 Ma in the second end-member model. The value of C is equal to the cumulative
785 stratigraphic onlap distances, but this overlooks the onlap distance driven by the growth of the
786 thrust wedges. Thus, the adopted values were probably too high, resulting in abnormally high
787 values of Te from ~ 26 Ma to ~ 5 Ma. Nonetheless, if convergence is completely overlooked, the
788 Te values for the ancient Tarim and Junggar lithospheres may be underestimated.

789 The modelling based on the modern tectonic subsidence profile predicts a β value of $\sim 7.8^\circ$
790 for the southern Tian Shan wedge, and it, together with the α value of 1.5° from the topographic
791 swath profile, constitute the wedge angle of 9.3° . The predicted β value of 7.0° and the observed
792 α value of 2.4° constitute the wedge angle of 9.4° for the northern Tian Shan wedge. A deep
793 seismic-reflection profile located ~ 600 km west of profile BB' ($\sim 76^\circ\text{E}$) reflects that the dip angle
794 of the basal décollement fault beneath the junction of the southwestern Tian Shan and Tarim
795 block is $\sim 8.0^\circ$ (Gao et al., 2013), close to the predicted β value of the southern Tian Shan thrust
796 wedge at $\sim 83^\circ\text{E}$ derived from our modelling.

797 According to our modelling, the wedge angles of the southern and northern thrust wedges of
798 the Tian Shan are approximately equal, 9.3° and 9.4° , respectively. This is different from the

799 geometry of doubly vergent orogens predicted by the sandbox and numerical simulations, which
800 has a significantly greater wedge angle for the retro-wedge than the pro-wedge (Vogt et al.,
801 2017; Sun et al., 2022), such as the Alpine orogen in Europe (Sinclair et al., 2005; Schlunegger
802 and Norton, 2015). This implies that both southern and northern Tian Shan could have
803 undergone evolution stages of retro-wedge and pro-wedge, resulting in the similarity in their
804 wedge angles. Specifically, when the Tarim block converged with the Tian Shan through
805 lithosphere indentation before the middle Miocene, the southern Tian Shan was characterized by
806 a retro-wedge, which tended to form a larger wedge angle, while the northern Tian Shan was
807 characterized by a pro-wedge, that tended to form a smaller wedge angle. After the middle
808 Miocene, the lithosphere subduction pattern replaced the convergence one, resulting in the
809 formation of southern Tian Shan as a pro-wedge and the northern Tian Shan as a retro-wedge
810 (Fig. 13). Consequently, the northern Tian Shan tended to form a relatively larger wedge angle,
811 eventually leading to the current situation in which the wedge angles of the southern and
812 northern Tian Shan are almost equal. It provides further validation for the transformation of the
813 deep architecture of the Tian Shan revealed by the migration and subsidence histories of the
814 coupled foreland basins.

815 **8 Conclusions**

816 The forelandward migration rates and subsidence history of the NTFB and SJFB are derived
817 from the seismic profiles across these basins. The linear fitting of the upper envelope of the
818 reflector terminations in profile AA' displays that the forebulge of the SJFB migrated northward
819 at ~3.1 mm/yr during the period of around 22-16 Ma. Based on the migration rates and observed
820 subsidence profiles, we used an elastic numerical model to describe the evolution of tectonic
821 subsidence in the foreland basins, combined with the formation of the southern and northern

822 Tian Shan wedges. The comparison between the migration and subsidence characters of NTFB
823 and SJFB reveals their plate settings, which could test the three models of lithospheric
824 architecture of the Tian Shan. Our analytical results and modelling show that the NTFB is
825 characteristic of the plate setting of a retro-foreland basin, while the SJFB resembled a pro-
826 foreland basin during the early-middle Miocene, which reveals the coeval uplift of the Junggar
827 lithosphere and the indentation of the Tarim lithosphere beneath the Tian Shan. The plate setting
828 of the NTFB and SJFB converted during the late Miocene to the present, implying a change in
829 the subduction polarity of the Tarim and Junggar lithospheres. The convergence pattern between
830 the Tarim lithosphere and the Tian Shan changed from lithospheric indentation to subduction,
831 implying a change in the subduction polarity of the Tarim and Junggar lithospheres.

832 The modelling of the subsidence histories of the NTFB and SJFB also indicates that both the
833 southern and northern Tian Shan had begun to uplift before the middle Miocene, with the
834 orogen's height reached half of its present elevation before the late Miocene. The propagation
835 rate of the northern Tian Shan has decreased since ~16 Ma, which may be related to the change
836 of the subduction polarity of the Junggar block beneath the northern Tian Shan wedge. The
837 propagation rates of the southern and northern Tian Shan have accelerated since the late
838 Miocene. Besides, although the uplift of the modern Tian Shan was initiated at around 26 Ma,
839 crustal shortening rate absorbed by the range was less than ~2 mm/yr between ~20 and ~12 Ma
840 according to our calculations, which is only ~4% of the total convergence rate between the
841 Indian and Eurasian continents during the same period. After the middle Miocene, it increased to
842 ~10-14 mm/yr, accounting for ~25-35% of the total convergence rate, documenting that the Tian
843 Shan has become one of the most active areas of intra-continental deformation in Asia since
844 then.

845 Our research has revealed the subduction polarity of the Tarim and Junggar blocks beneath
846 the middle segment of the Tian Shan. While the lateral variation of a lithospheric architecture
847 along the range has not been fully constrained, our research provides valuable insights and
848 information for understanding the lithospheric architecture of analogous complex
849 intracontinental orogens. Moreover, understanding the plate setting characteristics of the two
850 foreland basins could provide significant implications for hydrocarbon prospectivity.

851 **Data Availability**

852 The original seismic data supporting this research are owned by the China National
853 Petroleum Corporation (CNPC) with commercial restrictions and are not accessible to the public
854 or research community. The high-resolution seismic profiles used in this study can be accessed
855 via: <https://doi.org/10.6084/m9.figshare.22219000>

856 **Conflicts of Interest**

857 The authors declare that they have no conflicts of interest.

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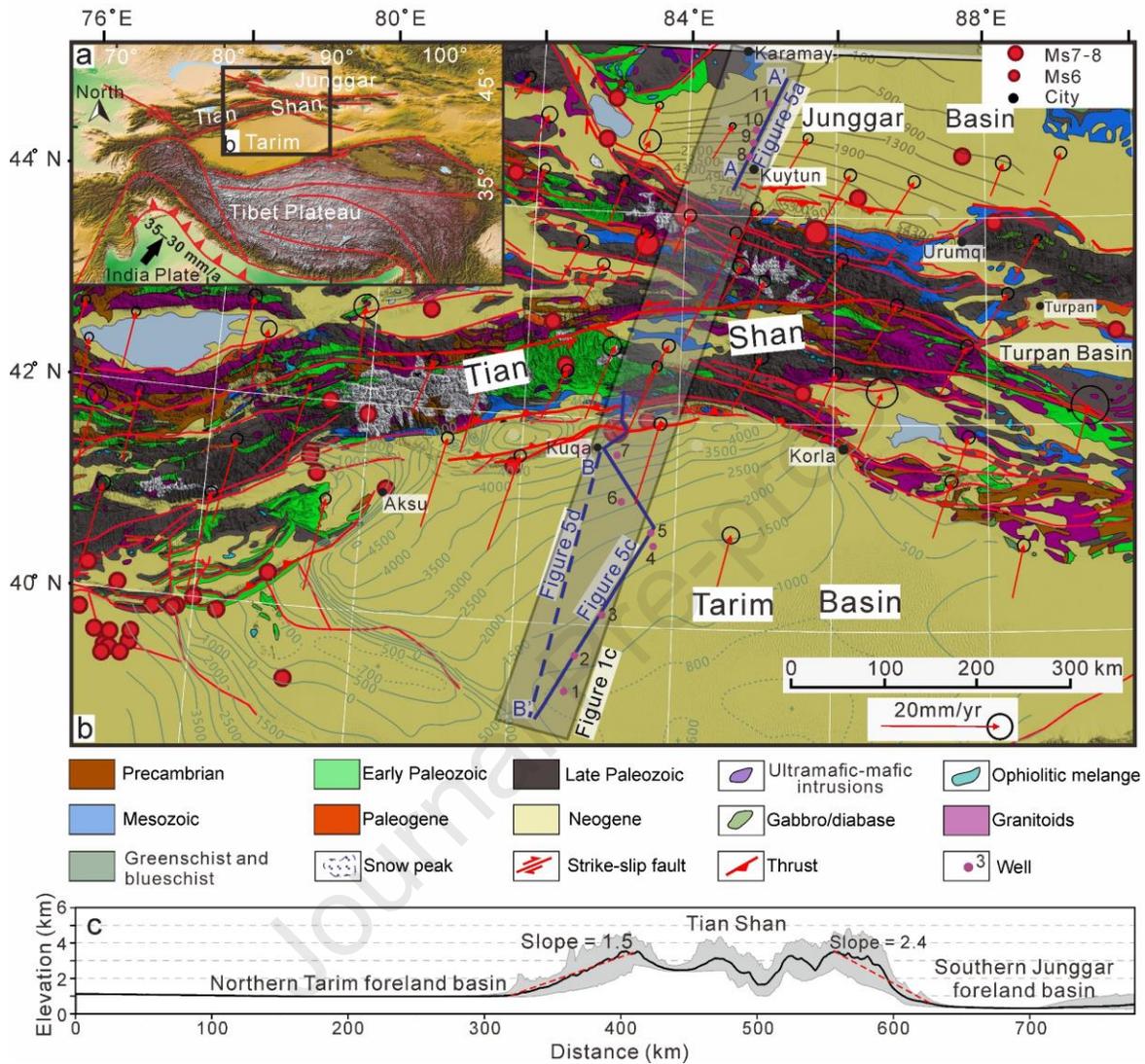
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- 1314

1315 **Figure 1**

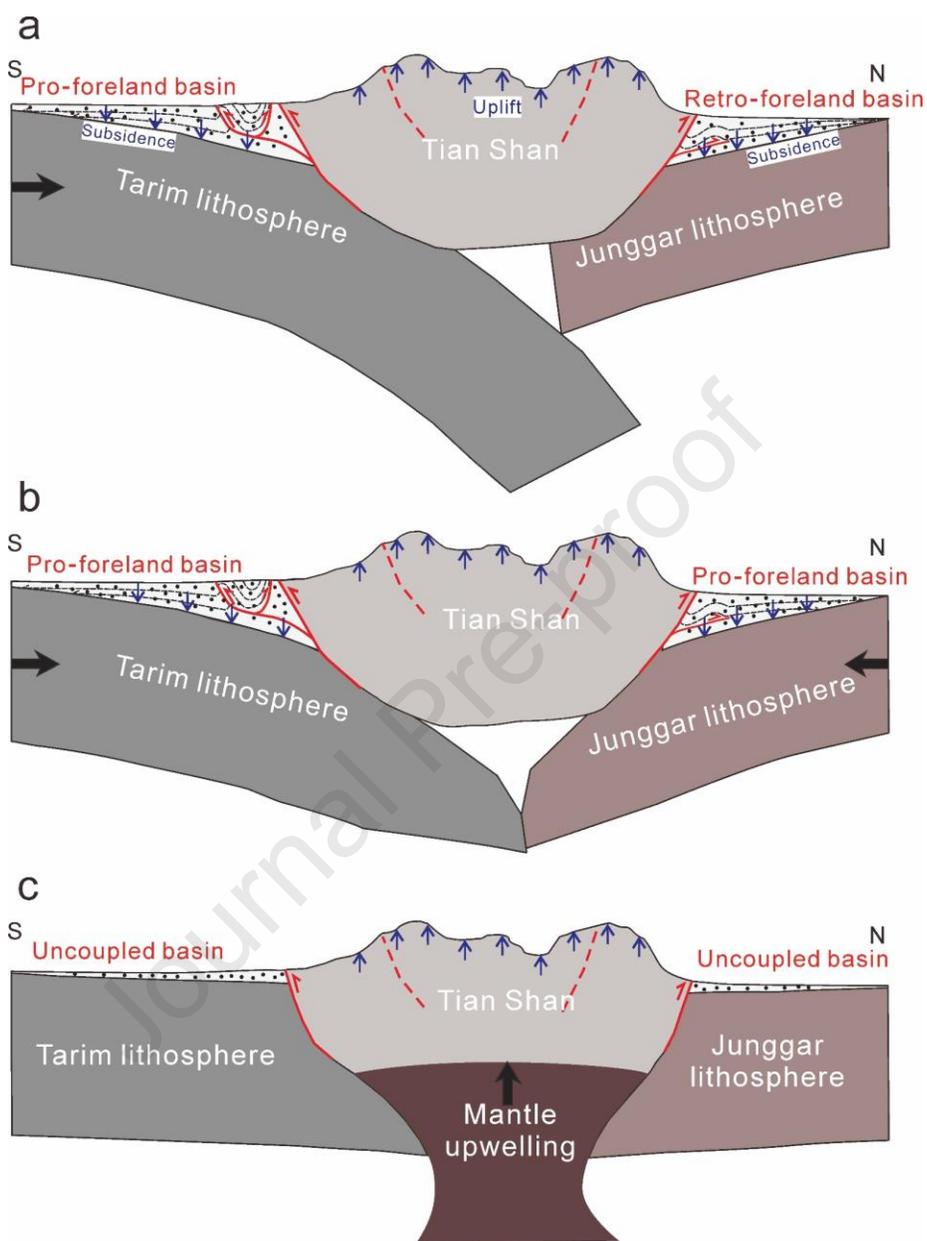
1316

1317 Figure 1 (a) The Tian Shan in the India-Asia collisional system. The direction and velocity of the
 1318 Indian tectonic plate is from Wang et al. (2001b). (b) Geological map of the middle segment of the Tian
 1319 Shan and the bilateral foreland basins on its southern and northern sides. The faults are drawn from Wu et
 1320 al. (2016). Thickness contours (unit: m) of the Neogene successions in the NTFB and the SJFB are from

1321 Jia et al. (1997) and Lv (2005), respectively. The solid dark blue line is the north-northeast trending
 1322 seismic profile across the NTFB and SJFB. The dashed dark blue line marks the location of the projected
 1323 section of the seismic profile across the NTFB. The red arrows show the GPS velocity field in the Tian
 1324 Shan with respect to stable Eurasia, and the GPS data with the error ellipses representing 70% confidence
 1325 are from Wang and Shen (2020). (c) A topographic swath profile across the Tian Shan, NTFB and SJFB

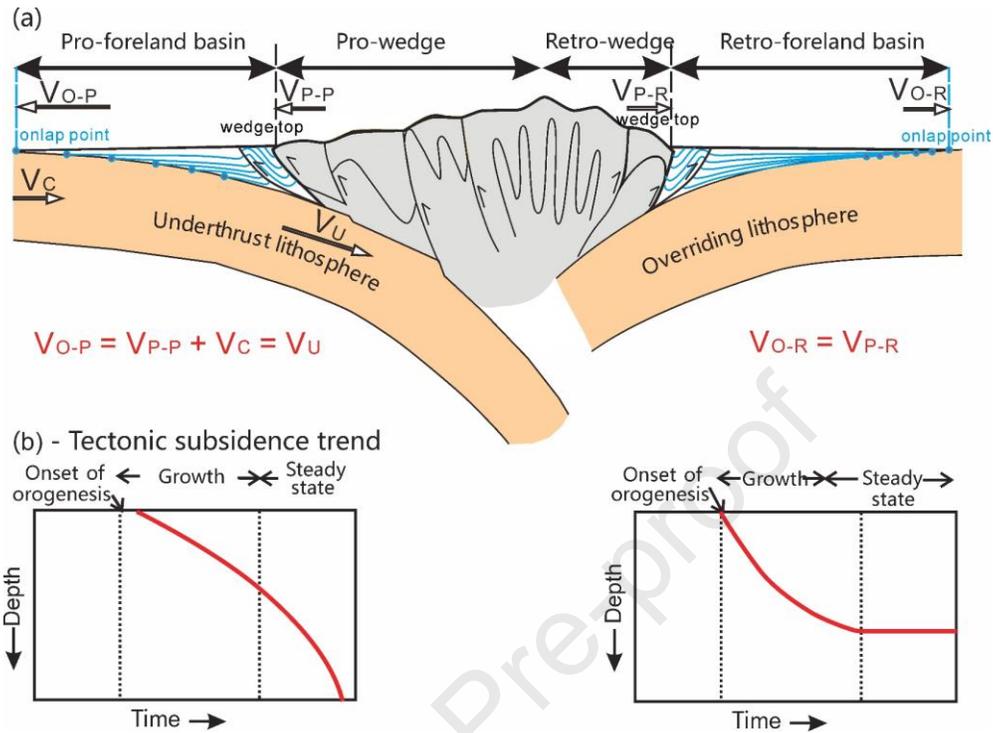
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(see Fig. 1b for location).

1327 **Figure 2**

1328
 1329 Figure 2 Schematic diagrams illustrating the three models of the lithospheric architecture of
 1330 the Tian Shan. (a) The Tarim lithosphere underthrusts beneath the Junggar lithosphere (Zhao et
 1331 al., 2003; Steffen et al., 2011; Gilligan et al., 2014). (b) The bidirectional underthrusting of the
 1332 Tarim and Junggar lithospheres contributed to the topographic growth of the Tian Shan (Li et al.,
 1333 2016a; Lü et al., 2019). (c) Mantle upwelling played a significant role in Tian Shan's uplift
 1334 (Roecker et al., 1993; Lei and Zhao, 2007).

1335

1336 **Figure 3**

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1338 Figure 3 (a) The contrasting characteristics of pro-/retro-foreland basins (modified after Naylor and

1339 Sinclair, 2008; Sinclair and Naylor, 2012). The pro-foreland foreland basin exhibits significant basin

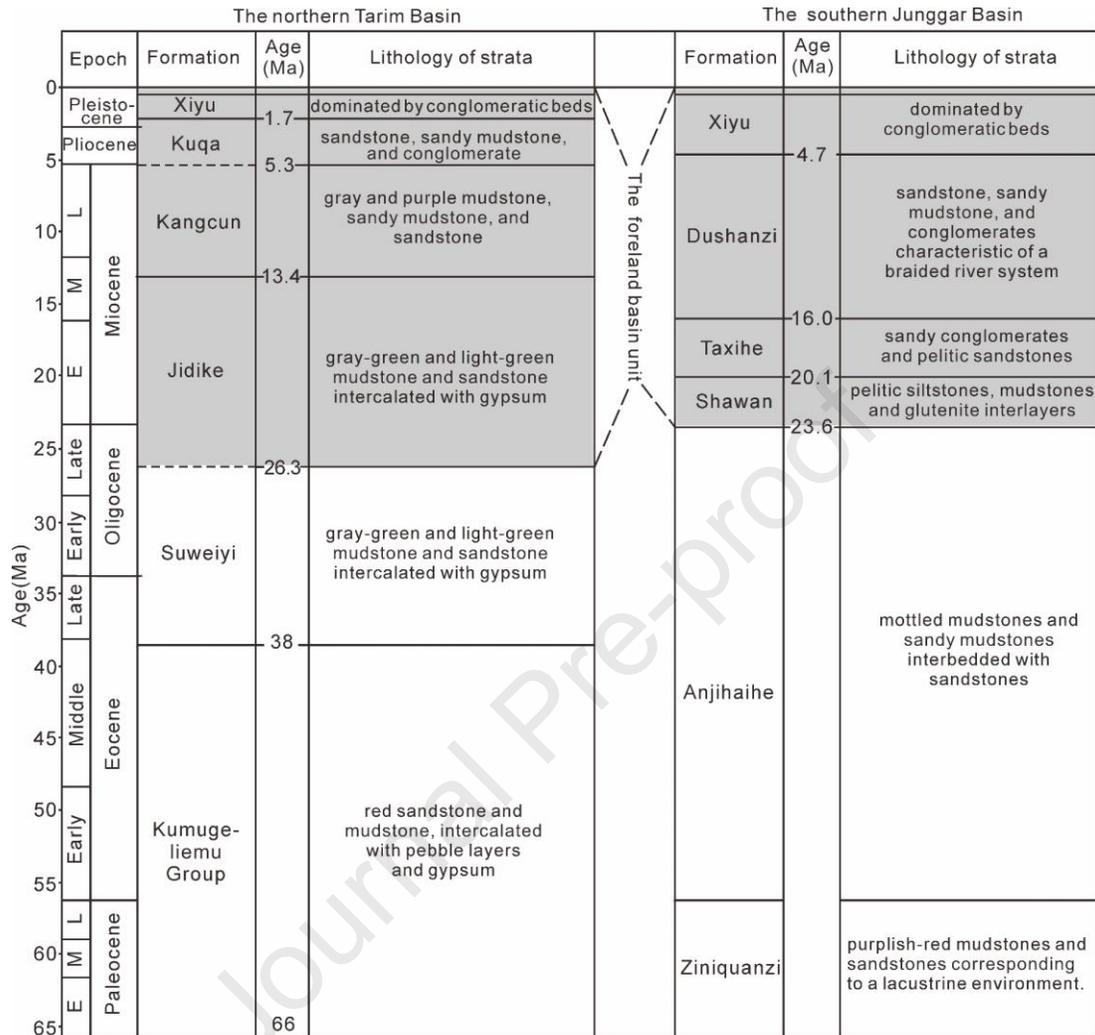
1340 onlap of the underthrust lithosphere, at a rate V_{O-P} equal to the sum of the plate convergence rate V_C and1341 the propagation rate of the pro-wedge V_{P-P} ; in contrast, the retro-foreland basin records little onlap except1342 in the early stage of growth. Its onlap rate V_{O-R} is equal to the propagation rate of the retro-wedge V_{P-R} .

1343 The pro-foreland basin records accelerated subsidence over a relatively short interval of orogenesis. In

1344 contrast, the retro-foreland basin records the full history of the basin with initial uniform subsidence

1345 during the growth of the mountain range.

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1347 **Figure 4**

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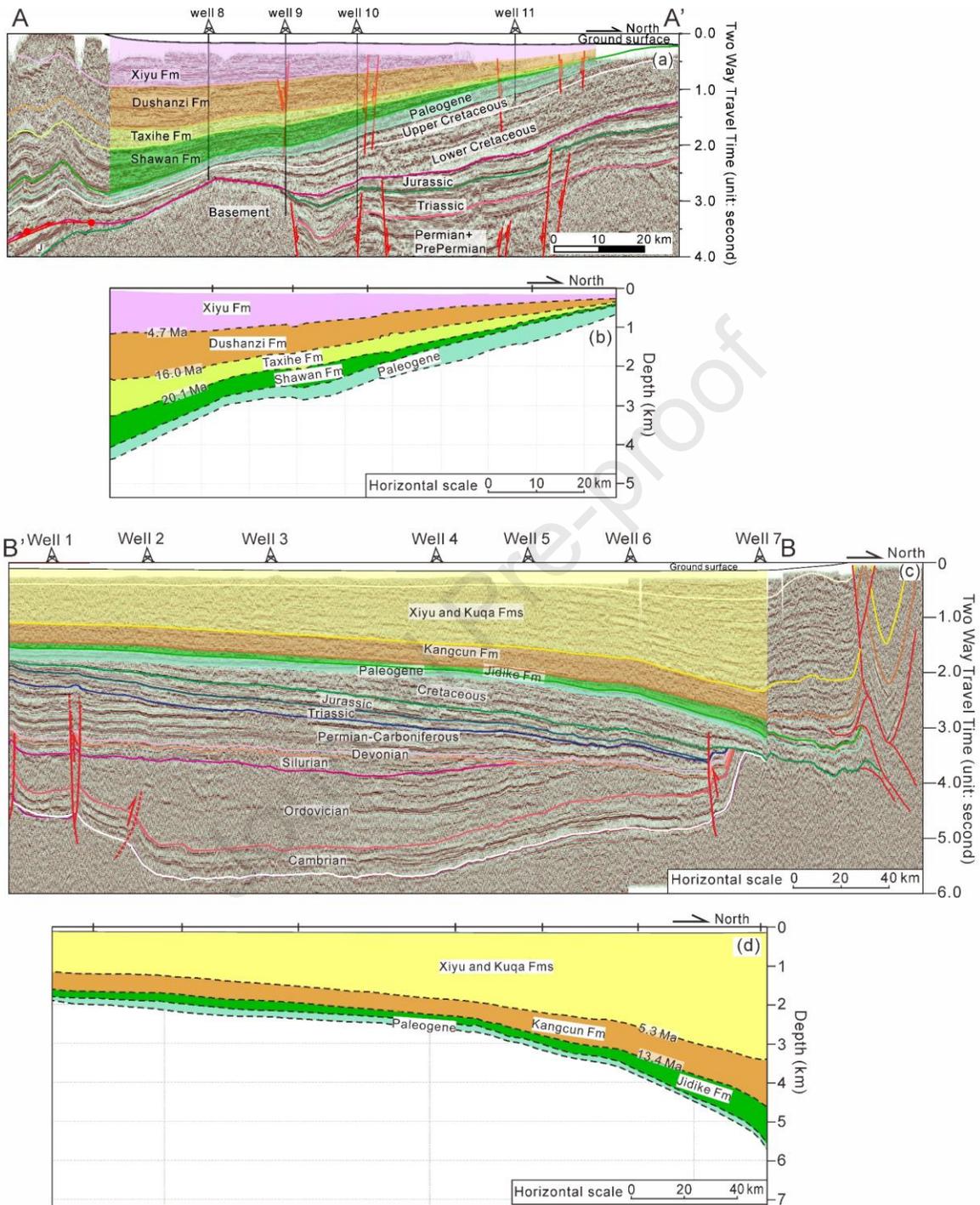
1349 Figure 4 Simplified lithostratigraphic charts of the NTFB and SJFB. The lithology of each formation

1350 is summarized by Zhang et al. (2004) and Yang et al. (2013). The ages of formations in the basins are

1351 constrained by magnetostratigraphic studies (Huang et al., 2006; Charreau et al., 2009; Lu et al., 2010;

1352 Zhang et al., 2014). The dotted lines indicate the unconformities between the formations.

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1354 **Figure 5**

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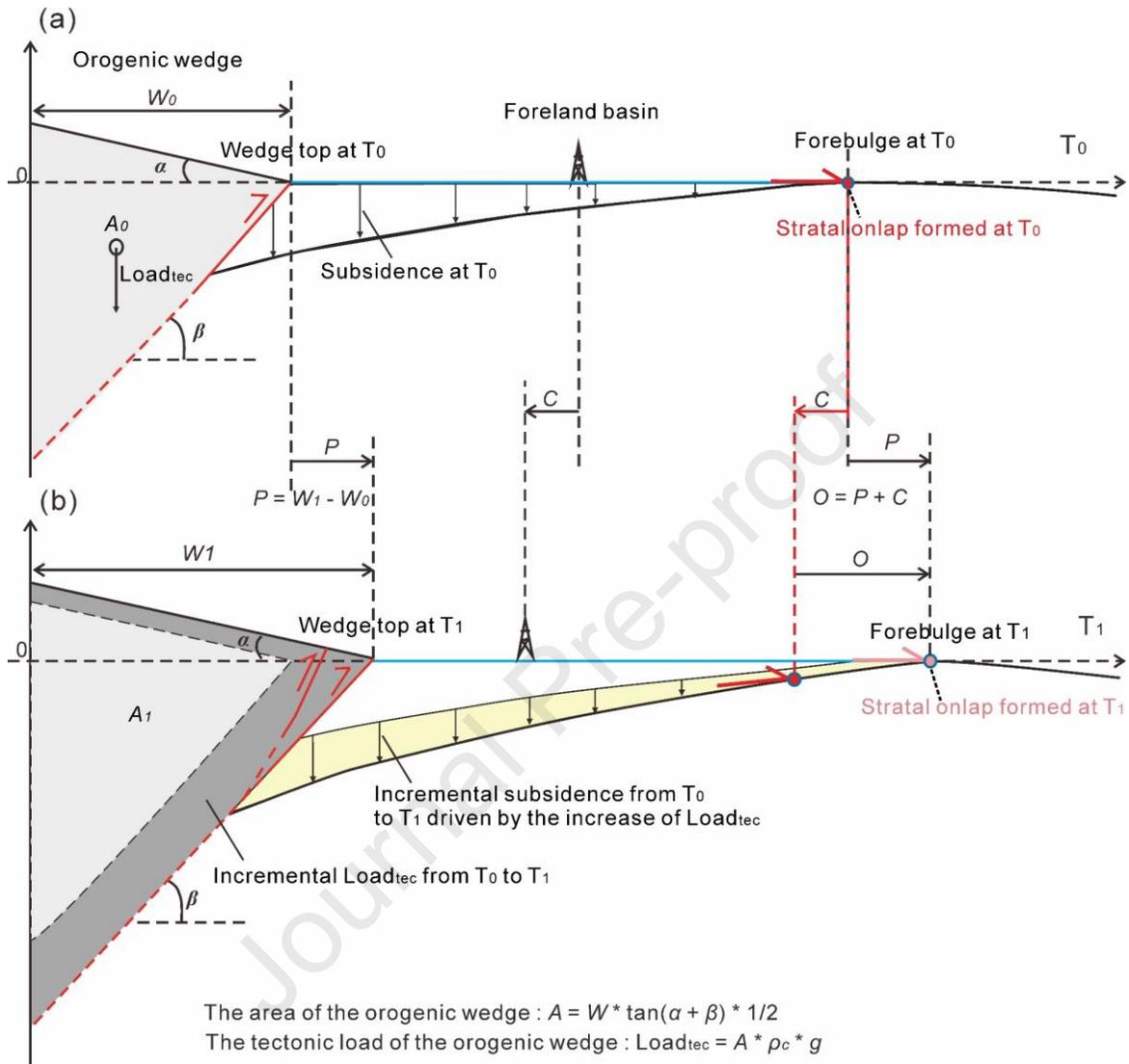
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Figure 5 The interpreted north-northeast trending seismic profiles across the SJFB (a) and the NTFB (c). See Figure 1b for their locations. Vertical exaggeration is ~15 times. These boundaries and faults are interpreted from well logging data near the profiles and interpretations of other seismic reflection profiles

1359 near the profiles from previous publications (Wang et al., 2013; Yu et al., 2014; Li et al., 2019). (b) The
1360 depth section of Figure 5c. (d) The projected depth section of the foredeep part in Figure 5a. See Figure
1361 1b for its location.

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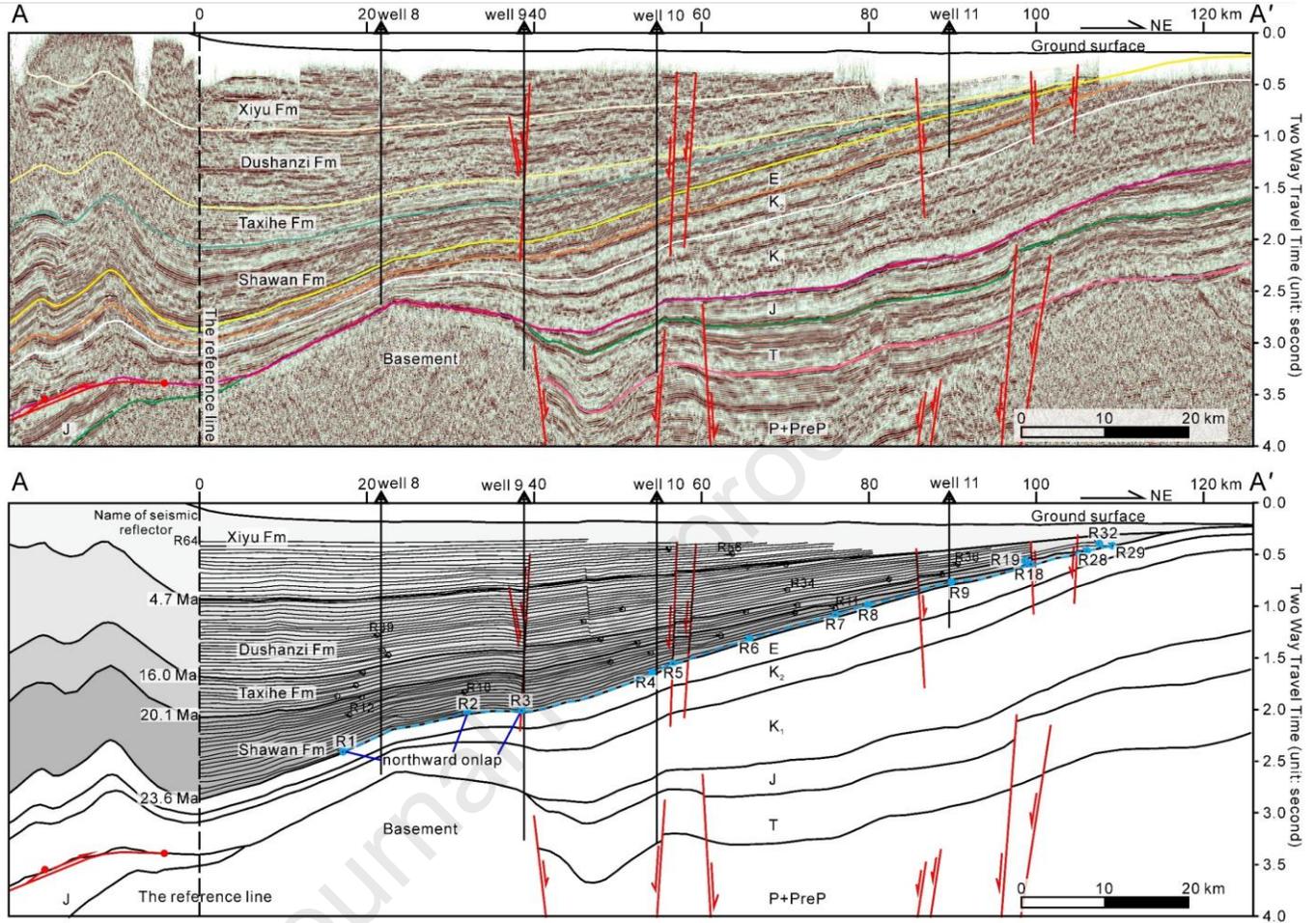
1362 **Figure 6**

1363

1364 Figure 6 (a) (b) A scheme of the numerical foreland basin model. In a foreland basin-thrust
 1365 wedge system, the increase of tectonic load (buildup) of the thrust wedge can cause flexure of
 1366 the underlying plate to form a foreland basin which is the subsidence in the coupled foreland
 1367 basin (DeCelles & Giles, 1996). Buildup of the thrust wedge also cause migration of the
 1368 forebulge to the foreland. Furthermore, underthrusting of the underlying plate beneath the orogen
 1369 lead to migration of the foreland basin to the foreland. Thus, the migration of the foreland basin
 1370 (O), recorded by the stratal onlaps, consists of the propagation of an orogenic wedge (P) and the

1371 convergence between the underlying plate and the thrust wedge (C) (DeCelles & DeCelles, 2001;
1372 Naylor and Sinclair, 2008; DeCelles, 2012), so $O = P + C$. Stratal onlaps in the foreland basin that
1373 records its lateral migration (e.g. Li et al., 2019; Wang et al., 2020). This type of onlaps has been
1374 identified in the seismic profile of Figs. 7 and S1. The W_0 and W_1 are the widths of the thrust wedge
1375 at T_0 and T_1 . The V_C , V_P and V_O are the velocity of the C , P and O , respectively.

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1376 **Figure 7**

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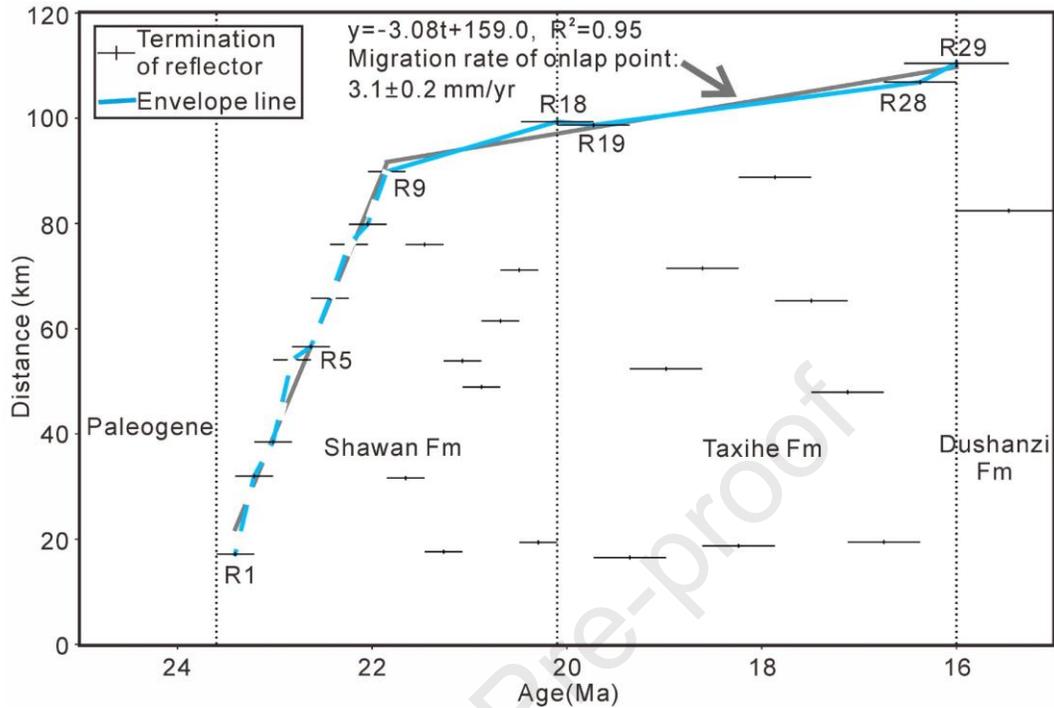
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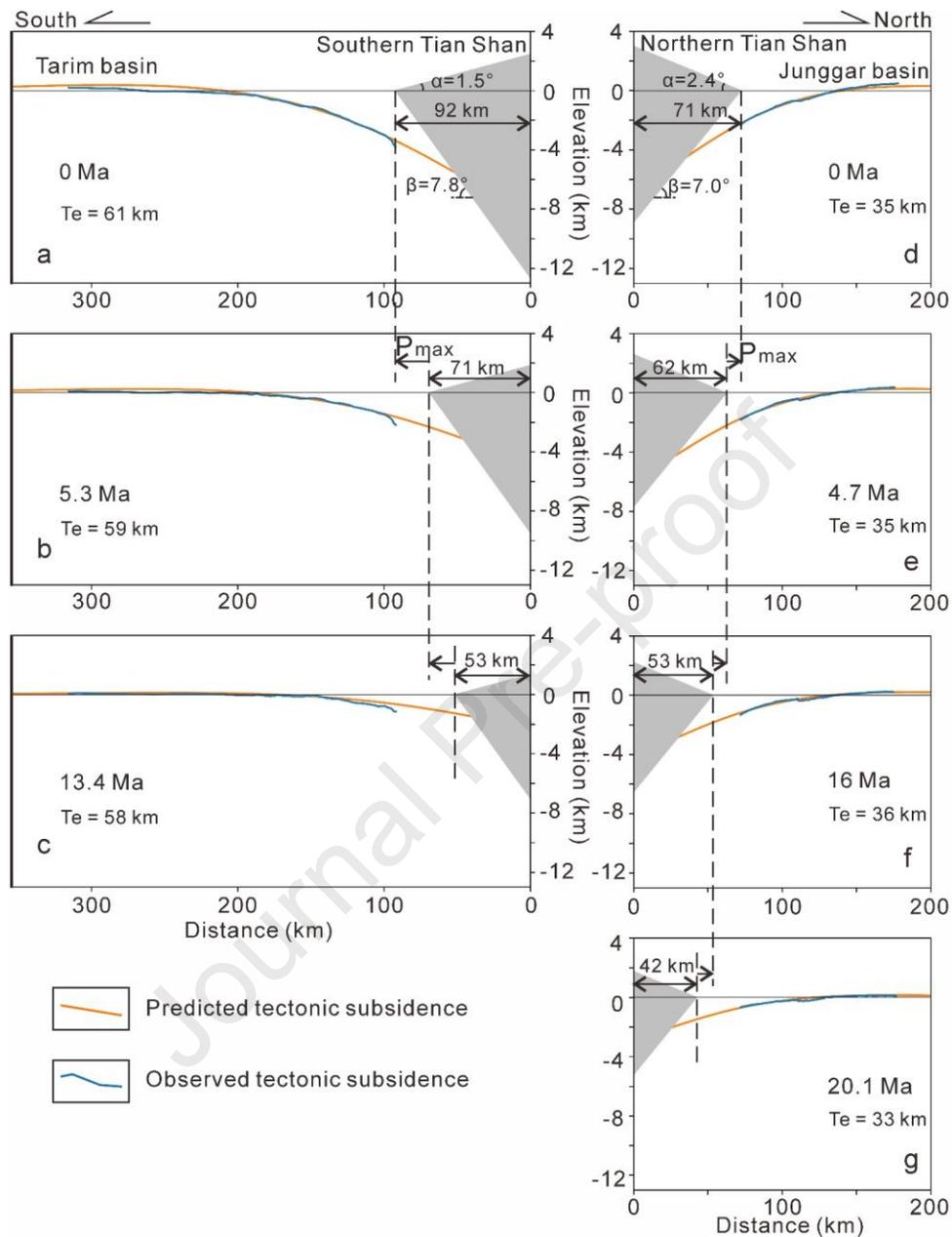
Figure 7 (a) Interpreted seismic profile crossing the foredeep of the SJFB (Wang et al., 2013). See Figure 1b for its location and Figure S1 for its large-scale version. Reflectors are marked with dark blue lines and named R1-R64. (b) Tracing lines of seismic reflectors in the Cenozoic. The arrows indicate reflector terminations. The onlap points toward the foreland are marked with a blue dashed line. The ages of bottoms of the Shawan, Taxihe, Dushanzi, and Xiyu Fms are dated by correlating the seismic reflectors with the magnetostratigraphic studies (Huang et al., 2006; Charreau et al., 2009; Lu et al., 2010). See Wang et al. (2013) for the correlation between the seismic profiles and the magnetostratigraphic results.

1386 **Figure 8**

1387

1388 Figure 8 Plot of reflectors ages of the Southern Junggar foreland sequences and distances from their
 1389 termination points to the northern Tian Shan wedge. Open symbols indicate values measured from the
 1390 reference line to terminations on Fig. 7. See Table S1 for all the measured values. The blue line is a
 1391 distribution envelope established by connecting the maximum values within about one million years. The
 1392 solid line is fitted by values connected by the dashed fold line. The envelope line of terminations indicates
 1393 migration of the forebulge.

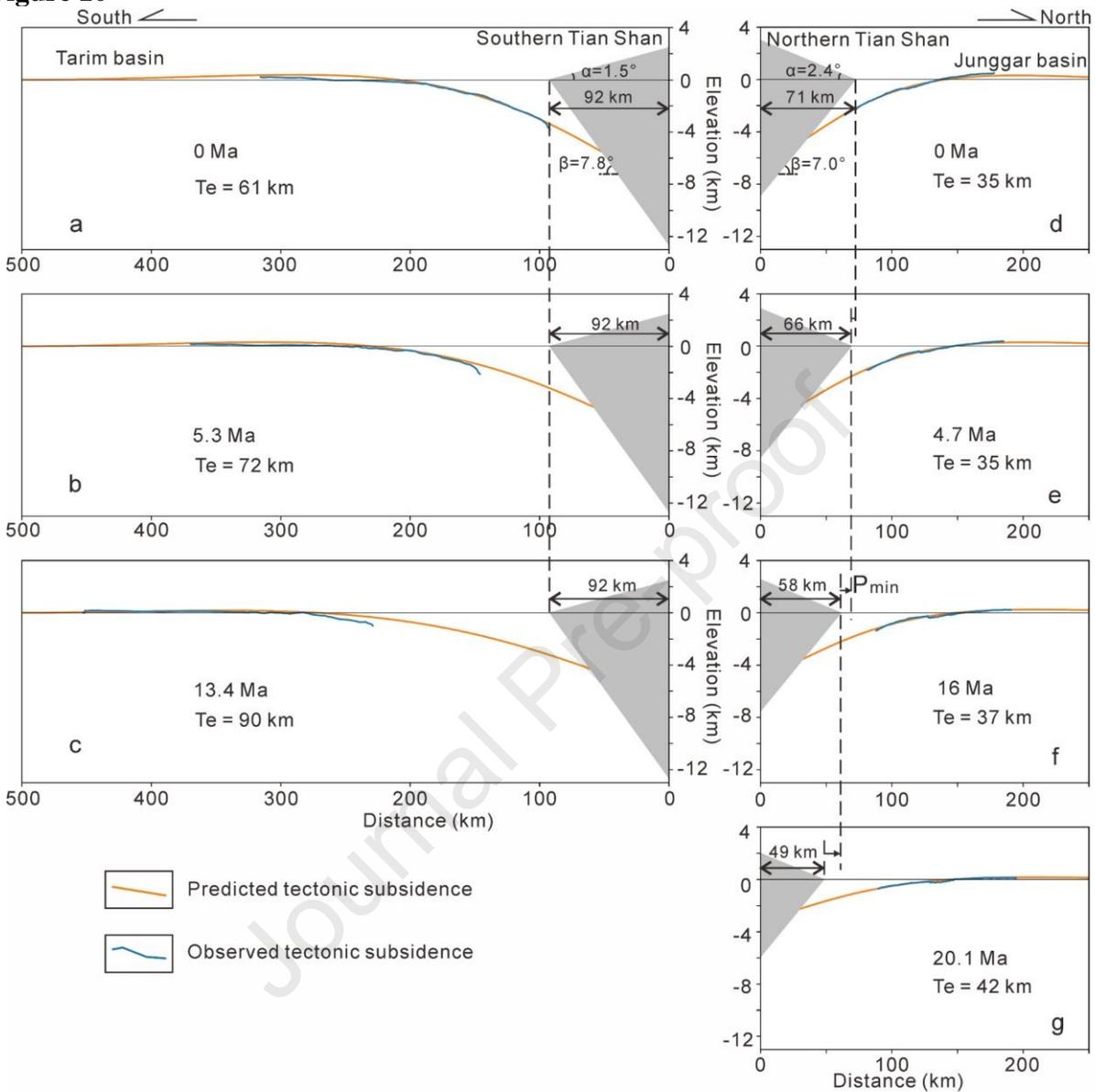
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1395 **Figure 9**

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1397 Figure 9 (a), (b) & (c) Modelled tectonic subsidence profiles across the NTFB at three moments from
 1398 the first end-member model. (d), (e), (f) & (g) Modelled tectonic subsidence profiles across the SJFB at
 1399 four moments from the first end-member model. The convergence distance (C in Fig. 6) between the
 1400 thrust wedge and the basin basement in the model is set to zero. The grey triangles represent the predicted
 1401 topographic loads of the southern and northern Tian Shan thrust wedges. The variation of the triangle
 1402 widths indicates the maximum value of propagation (P) of the southern and northern Tian Shan wedges.

1403

Figure 10

1404

1405 Figure 10 (a), (b) & (c) Modelled tectonic subsidence profiles across the NTFB at three moments

1406 from the second end-member model with a theoretical maximum value of the horizontal convergence

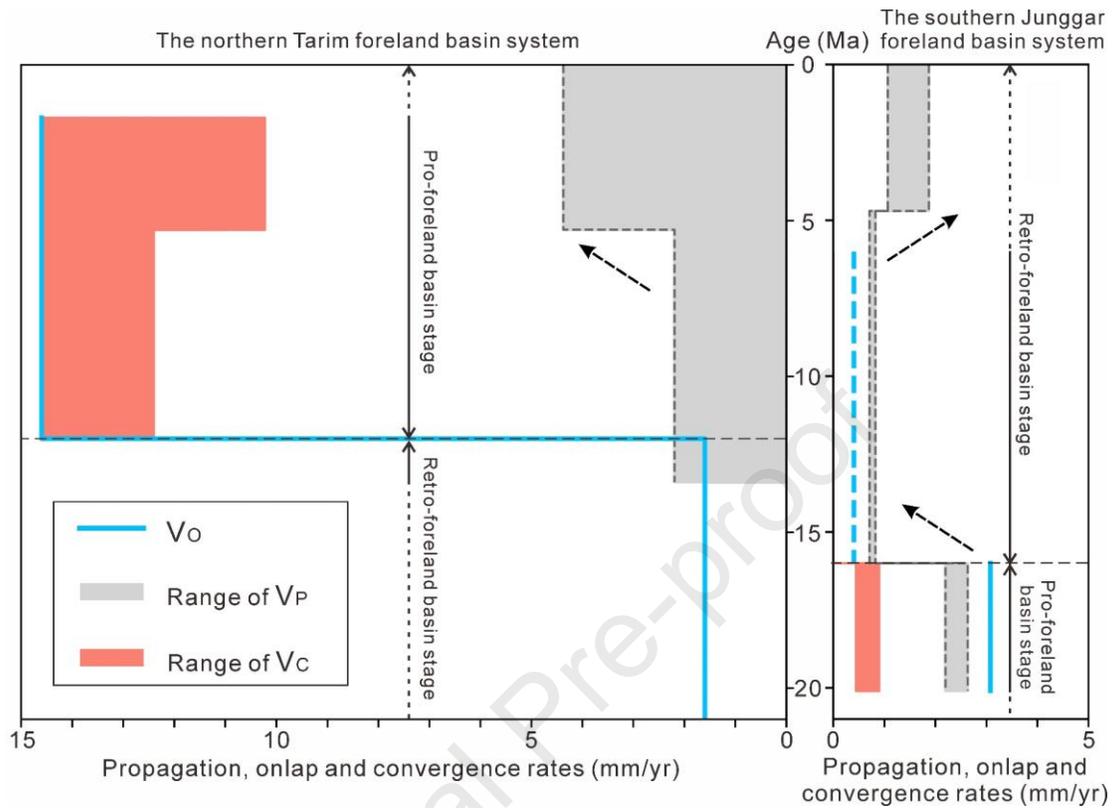
1407 between the thrust wedge and basin basement equaling to the migration distance of the foreland basins.

1408 (d), (e), (f) & (g) Modelled tectonic subsidence profiles across the SJFB at four moments from the second

1409 end-member model. The grey triangles represent the predicted topographic loads of the southern and

1410 northern Tian Shan thrust wedges. The variation of the triangle widths indicates the minimum value of

1411 propagation (P) of the southern and northern Tian Shan wedges.

1412 **Figure 11**

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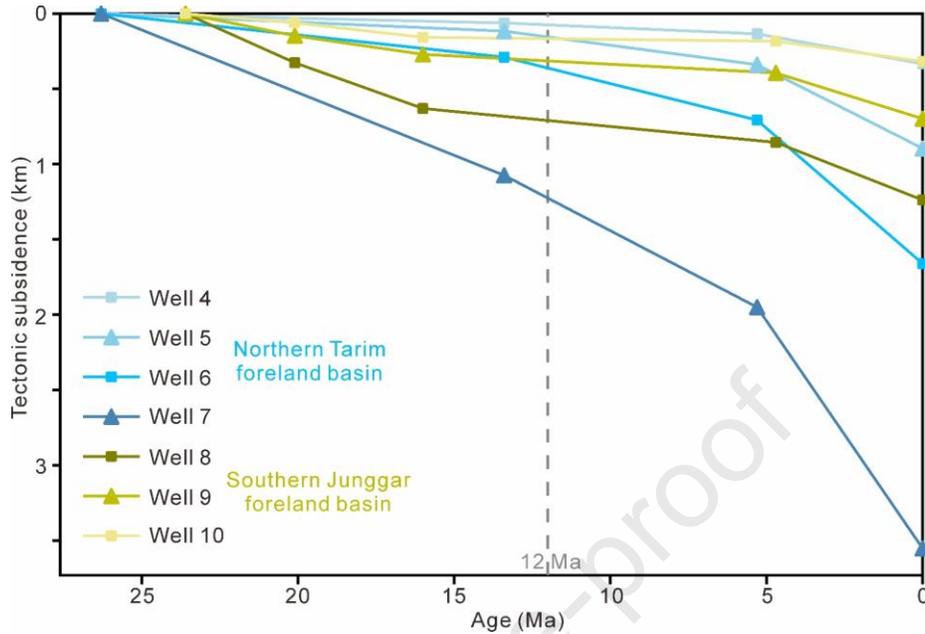
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Figure 11 The evolution of the forelandward onlap rate, propagation rate of the thrust wedge and the convergence rate in the NTFB and SJFB systems. The dash blue line in the plot of the SJFB represents the migration rate of the conglomerate-sandstone transition in the foreland sequence to the ~40 km west of profile BB' (Li et al., 2022). The black arrows indicate the changes in the propagation rate of the predicted topographic loads of the southern and northern Tian Shan wedges.

1420 **Figure 12**

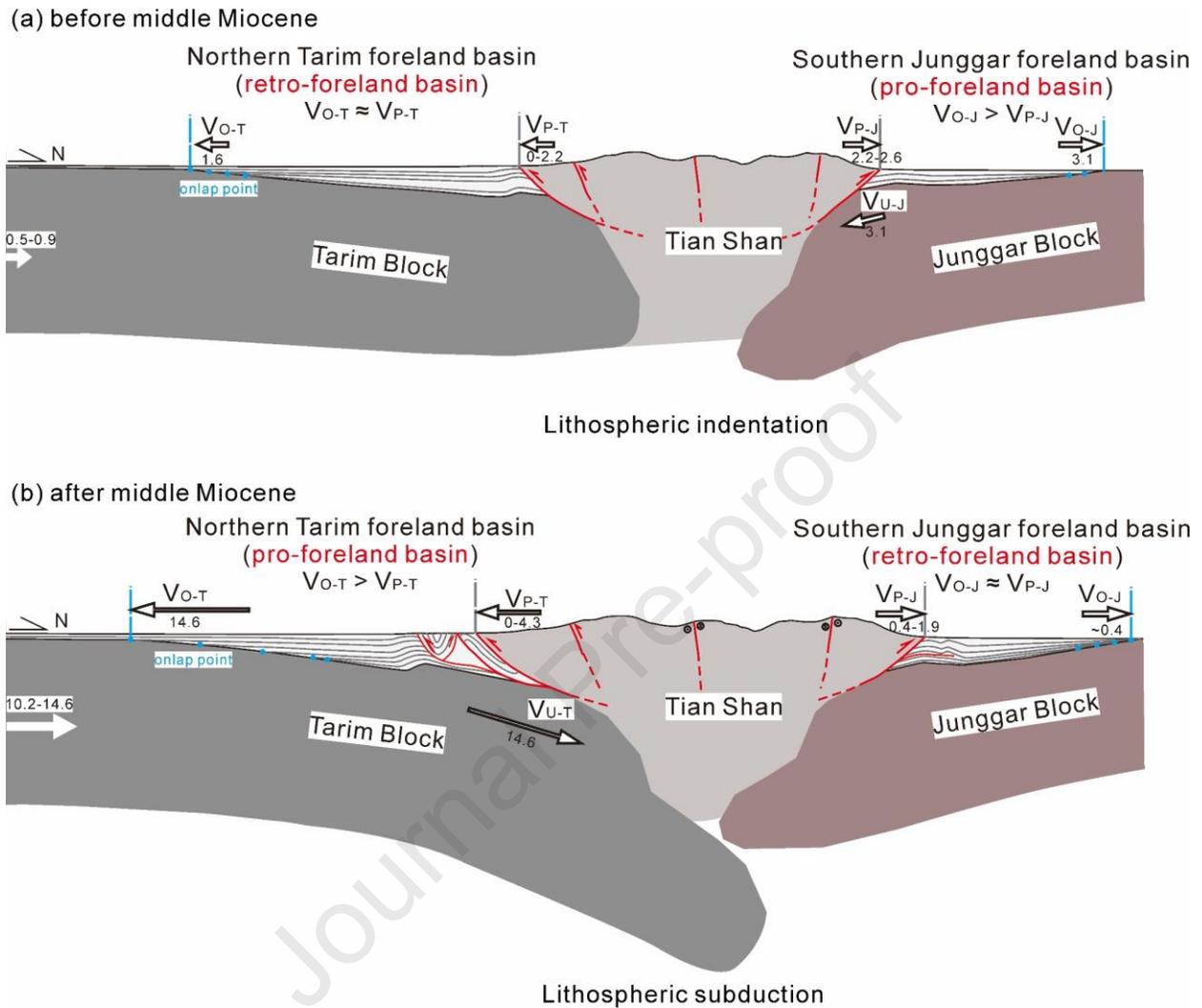
1421

1422 Figure 12 Neogene tectonic subsidence curves of wells 4, 5, 6 and 7 in the NTFB and wells 8, 9 and
 1423 10 in the SJFB. Well positions are shown in Figs. 1b and 4. The tectonic subsidence curve is yielded by
 1424 flexural back stripping, paleo-bathymetric corrections and eustatic corrections using data from the wells.

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The average tectonics subsidence rates of the seven wells are listed in Table 3.

1426

1427 **Figure 13**

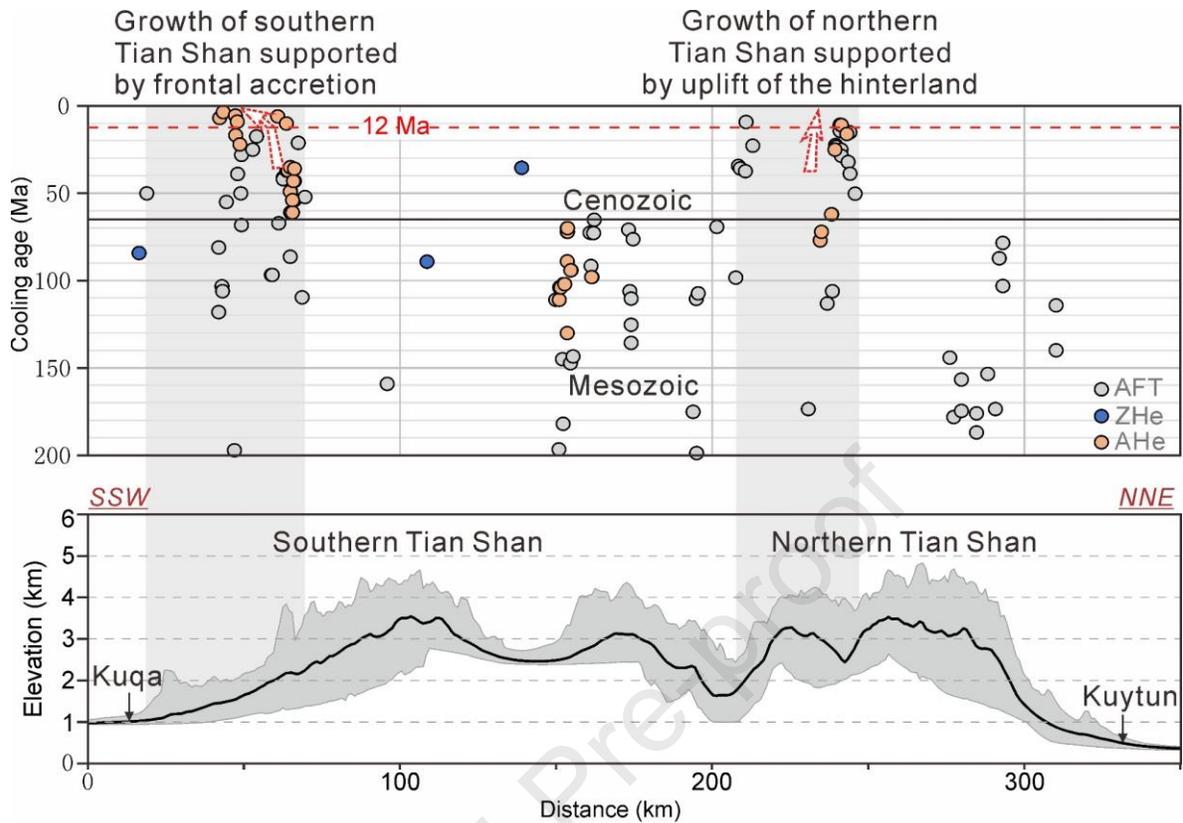
1428

1429 Figure 13 The deep structure of the middle segment of the Tian Shan unraveled by the evolution of

1430 the bilateral foreland basins. The length of the arrows represents the relative velocity of the propagation

1431 rate of the thrust wedge (V_{P-T} , V_{P-J}), the onlap rate of the foreland sequence (V_{O-T} , V_{O-J}) and the1432 underthrusting rate (V_{U-T} , V_{U-J}) in the NTFB and SJFB.

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Figure 14 The Cenozoic cooling ages obtained around and in the same swath profile across the middle segment of the Tian Shan, location is referred in Figure 1b (data sources: Dumitru et al., 2001; Yang et al., 2003; Zhang et al., 2007; Du et al., 2007; Wang et al., 2008; 2009; Jolivet et al., 2010; Chang et al., 2017a). The dashed arrows show the incoming flux in the pro-side and retro-side. Table of individual ages and their associated metadata can be found in Tables S3 in the Supplementary material. AFT - apatite fission-track, ZHe - zircon (U-Th)/He and AHe - apatite (U-Th)/He.

1442 **Table 1**

1443 Table 1 Lithological and decompaction parameters used in back stripping (Sclater and Christie, 1980).

Lithology	Compaction decay length D^* ($10^5/\text{cm}^{-1}$)	Initial porosity ϕ_0	Sediment grain density ρ_s (g cm^{-3})
Sandstone	0.27	0.49	2.65
Shale	0.51	0.63	0.72
Shaly sand	0.39	0.56	2.68

1444

1445 **Table 2**

1446 Table 2 The onlap rates of the foreland sequence, propagation rate of the thrust wedge and the crustal
 1447 shortening rate in the Northern Tarim and southern Junggar foreland basin systems. The stratal onlap rates
 1448 are determined by the interpretations of the seismic profiles across the NTFB (Li et al., 2019) and SJFB.

Northern Tarim foreland basin-thrust wedge system					
Time (Ma)	Propagation rate of thrust wedge (mm/yr)	Time (Ma)	Stratal onlap rate (mm/yr)	Time (Ma)	Convergence rate (mm/yr)
0–5.3	0–4.4	1.7–12.0	14.6	1.7–5.3	10.2–14.6
5.3–13.4	0–2.2	12.0–26.0	1.6	5.3–12.0	12.4–14.6
				12.0–13.4	0–1.6
Southern Junggar foreland basin-thrust wedge system					
Time (Ma)	Propagation rate of thrust wedge (mm/yr)	Time (Ma)	Stratal onlap rate (mm/yr)	Time (Ma)	Convergence rate (mm/yr)
0–4.7	1.1–1.9				
4.7–16.0	0.7–0.8	4.7–16.0	0.4*	4.7–16.0	0
16.0–20.1	2.2–2.6	16–20.1	3.08	16.0–20.1	0.5–0.9

1449 *This is the forelandward migration rate of the conglomerate-sandstone transition in the foreland
 1450 sequence of the SJFB, which reveals the onlap rate of the foreland sequences (Li et al., 2022).

1451

1452 **Table 3**

1453 Table 3 The tectonic subsidence rates of Wells 4, 5, 6 & 7 in the NTFB and Wells 8, 9 & 10 in the SJFB

1454 from back stripping. Well positions are shown in Figs. 1b and 4.

Northern Tarim foreland basin				
Time (Ma)	Tectonic subsidence rate (mm/yr)			
	Well 4	Well 5	Well 6	Well 7
0–5.3	37.5	104.9	180.0	302.5
5.3–13.4	8.9	27.5	51.6	108.1
13.4–26.3	4.8	9.0	11.0	40.8
Southern Junggar foreland basin				
Time (Ma)	Tectonic subsidence rate (mm/yr)			
	Well 8	Well 9	Well 10	
0–4.7	81.5	64.7	28.5	
4.7–16.0	17.8	11.0	2.3	
16.0–20.1	80	28.8	21.0	
20.1–23.6	93.1	43.4	20.1	

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Highlights:

- The forebulge of the southern Junggar foreland basin (SJFB) migrated northward at ~ 3.1 mm/yr during ~ 22 – 16 Ma.
- The northern Tarim foreland basin was a retro-foreland basin, while SJFB was a pro-foreland basin before the middle Miocene, but they converted later.
- The Tarim block was an overriding plate before the middle Miocene, while the Junggar block was an underthrusting plate, but they switched roles after the middle Miocene.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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