## Statement

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# Structural controls on earthquake rupture revealed by the 2020 $M_w$ 6.0 Jiashi earthquake (Kepingtag belt, SW Tian Shan, China)

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**SUMMARY**

The Kepingtag (Kalpin) fold-and-thrust belt of the southern Chinese Tian Shan is characterized by active shortening and intense seismic activity. Geological cross-sections and seismic reflection profiles suggest thin-skinned, northward-dipping thrust sheets detached in an Upper Cambrian décollement. The January 19 2020 $M_w$ 6.0 Jiashi earthquake provides an opportunity to investigate how coseismic deformation is accommodated in this structural setting. Coseismic surface deformation resolved with Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) is centered on the back limb of the frontal Kepingtag anticline. Elastic dislocation modelling suggests that the causative fault is located at $\sim$7 km depth and dips $\sim$7° northward, consistent with the inferred position of the décollement. The narrow slip pattern (length $\sim$37 km but width only $\sim$9 km) implies that there is a strong structural or lithological control on the rupture extent, with up-dip slip propagation possibly halted by an abrupt change in dip angle where the Kepingtag thrust is inferred to branch off the décollement. A depth discrepancy between mainshock slip constrained by InSAR and teleseismic waveform modelling ($\sim$7 km) and well-relocated aftershocks ($\sim$10–20 km) may imply that sediments above the décollement are velocity strengthening. We also relocate 148 regional events from 1977 to 2020 to characterize the broader distribution of seismicity across the Kepingtag belt. The calibrated hypocenters combined with previous teleseismic waveform models show that thrust and reverse faulting earthquakes cluster at relatively shallow depths of $\sim$7–15 km but include abundant out-of-sequence events both north and south of the frontal Kepingtag fault.

**Key words:** Radar interferometry, Asia, Earthquake source observations, Waveform inversion, Folds and folding, Intra-plate processes

## 1 INTRODUCTION

Late Cenozoic crustal deformation in central Asia is dominated by reverse and strike-slip faulting and folding within and around the margins of the Tian Shan mountains. Geodetic data indicate that $\sim$6–9 mm/yr of the present-day shortening occurs across the Chinese Tian Shan between the northwestern Tarim Basin and southern Kyrgyzstan (Reigber et al., 2001). The Kepingtag (Kalpin) fold-and-thrust belt has developed along part of the southern margin of this range (Fig. 1). This actively-deforming belt is one of the most earthquake-prone regions of the Tian Shan and of China. In recent years, this intense seismicity has attracted much interest in the deformation style, rate and other characteristics of the Kepingtag belt (Allen et al., 1999; Zhou & Xu, 2000; Zhang et al., 2008; Yang et al., 2002, 2006; Ran et al., 2006). Furthermore, it is one of the few parts of Tian Shan where deformation can be seen stepping into the surrounding foreland, with emergent thrust sheets predominantly vergent toward the Tarim basin in the south. Therefore, the deformation of the Kepingtag belt can also inform how the mountain ranges of southern Tian Shan grow through time.

Fold-and-thrust belts pose distinct challenges for seismic hazard assessment since much of the active faulting is buried. This is exemplified by iconic earthquakes such as the 1978 $M_s$ 7.4 Tabas,

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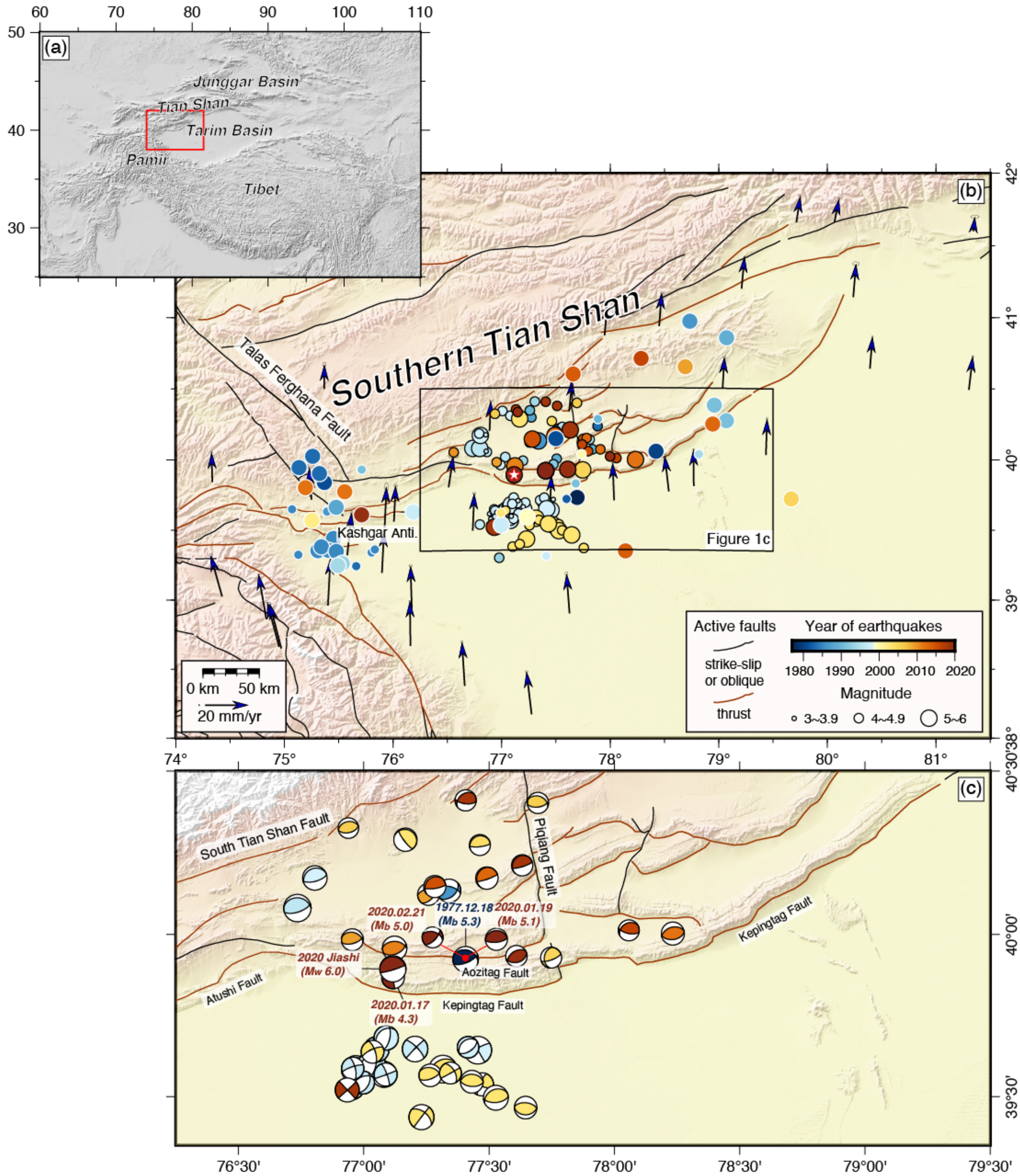


**Figure 1.** Tectonics and seismicity of the study area. (a) Shaded relief of the Himalayan orogeny with the location of panel (b) outlined in red. (b) Tectonic map of the southern Tian Shan. Instrumental seismicity is scaled by magnitude and colored by year from 1977.12.18 to 2020.02.21. Our own relocated epicenters are shown with black outlines, while those from the United States Geological Survey (USGS) have white outlines. The white star is the relocated epicenter of the 2020 January 19 Jiashi mainshock. Active faults are from the online database provided by the Institute of Geology, China Earthquake Administration (http://www.neotectonics.cn/arcgis/apps/webappviewer/index.html?id=3c0d8234c1dc43eaa0bec3ea03bb00bc) and Global Navigation Satellite Systems (GNSS) velocities relative to stable Eurasia are from Wang et al. (2020). (c) Topography, active faults, and earthquakes of the Kepingtag fold-and-thrust belt. Focal mechanisms are from teleseismic body-waveform modelling studies or the Global Centroid Moment Tensor (CGMT) catalog (see Table 1 for details). They are plotted at our relocated epicenters, coloured by year and scaled by magnitude.

Iran earthquake (Walker et al., 2003) and the 1987 $M_w$ 5.9 Whittier and 1994 $M_w$ 6.7 Northridge, California earthquakes (e.g., Davis et al., 1989; Jones et al., 1994), each characterized by shallow folding and blind faulting without accompanying surface rupture. There are many other examples of large earthquakes that ruptured faults were not previously mapped, and where historical and instrumental records were too short to have revealed the associated seismic hazard beforehand. Furthermore, fold-and-thrust belts contain a wide range of fault structures including décollements and ramp-and-flat thrusts, and it is often not clear which of these host large earthquakes and which creep aseismically (e.g., Copley, 2014; Ainscoe et al., 2017; Mallick et al., 2021). It is also important to consider how subsurface structure and stratigraphy may influence rupture extents, and thus potential earthquake magnitudes (e.g., Elliott et al., 2011; Nissen et al., 2011).

On January 19 2020 at 13:27:56 UTC, a $M_w$ 6.0 earthquake struck near Jiashi in the western Kepingtag belt ($\sim$39.83°N, 77.21°E) (Fig. 1), causing intense ground shaking and damage to hundreds of buildings. A regional seismic network recorded 1,639 aftershocks as of February 11 2020 (Ran et al., 2020), with the largest ($M_b$ 5.1) occurring $\sim$1 hour after the mainshock. This sequence provides an opportunity to investigate patterns of seismicity and deformation in this region. Routine teleseismic moment tensor solutions for the mainshock from the U.S. Geological Survey (USGS) and the Global Centroid Moment Tensor project (GCMT) implicate thrust or reverse faulting, but exhibit discrepancies of tens of degrees in strike, dip, and rake and of several kilometers in centroid depth and location. This makes it difficult to associate the earthquake with specific faulting or characterize its tectonic implications without further investigation (Engdahl et al., 2006; Weston et al., 2011; Wimpenny & Scott Watson, 2020).

Fortunately, Interferometric Synthetic Aperture Radar (InSAR) observations and modelling can provide more precise constraints on fault geometries and depth extents of large, shallow continental earthquakes (e.g., Elliott et al., 2016). Furthermore, growing compilations of seismic phase arrival times can help relocate earthquake hypocenters more accurately which, in conjunction with InSAR slip models, can provide additional information on rupture directivity (e.g., Pousse-Beltran et al., 2020). In this paper, we map the surface deformation of the 2020 Jiashi earthquake using the Sentinel-1 InSAR imagery and characterize its subsurface fault geometry and slip distribution using elastic dislocation modelling. We provide an independent check on its mechanism and centroid depth using teleseismic body waveform modelling and pinpoint its hypocenter using a calibrated, multi-event relocation. We relate some striking features of the surface deformation and slip model to the subsurface structure of the Kepingtag belt. Our multi-event relocation also allows us to re-assess earlier instrumental earthquakes in this region. These new results are used to reevaluate the active tectonics and seismic hazard of the Kepingtag belt.

## 2 TECTONIC SETTING

The Tian Shan in Central Asia originally formed in the Paleozoic, and most of the present topography of the mountain ranges resulted from Cenozoic reactivation as a result of the India-Eurasia collision (Windley et al., 1990; Hendrix et al., 1992; Avouac & Tapponnier, 1993; Burchfiel et al., 1999). Over time, the deformation has propagated outward into the Tarim and Junggar basins, where along certain parts of the Tian Shan margins, intense folding and faulting have created sets of narrow ridges. The Kepingtag fold-and-thrust belt, located along the arid southern margin of the Chinese Tian Shan, offers one of the clearest examples of this basinward migration of active deformation (Fig. 1b).

### 2.1 Geology of the Kepingtag belt

About 200 km long by 50 km wide and trending WSW–ENE, the Kepingtag belt consists of fault-related folds associated with a series of south-verging, imbricated thrust stacks (Allen et al., 1999). Folded strata are composed of Cambrian–Ordovician Qiulitag group limestones, Middle Ordovician Saergan group limestone and dolomite, Silurian Kepingtag group sandstone, Devonian sandstone, Carboniferous Kangkelin group sandstone, lower Permian limestone, and Paleogene–Neogene Wuqia group sandstone and conglomerate (Chen et al., 2006; Yang et al., 2010). The thickness of the upper Paleozoic strata in the Kepingtag belt increases from about 2 km in the south to greater than 4 km in the north (Yin et al., 1998). There is a major angular unconformity between the Paleozoic strata and the Cenozoic foreland basin deposits, with the near absence of Mesozoic sedimentary rocks implying significant Paleozoic crustal shortening.

**Table 1.** Earthquake source parameters in the Kepingtag belt and its foreland. Relocated hypocenters are from this study. The focal depth (FD) is followed by a superscript letter describing how it was calibrated: $d$ = teleseismic depth phases, $l$ = local-distance readings, $n$ = near-source station readings, and $c$ = cluster default depths. Focal mechanisms are taken from *(1)* Fan et al. (1994), *(2)* Sloan et al. (2011), *(3)* Ghose et al. (1998), *(4)* the Global Centroid Moment Tensor (GCMT) catalogue, and *(5)* this study. The centroid depth (CD) is also given a superscript letter that describes whether it was obtained by modelling ($t$) teleseismic body-waveforms, ($d$) teleseismic depth phases, ($r$) regional waveforms, or ($i$) = InSAR surface displacements. Where only a less reliable GCMT centroid depth is available, we mark the solution with an asterisk.

| | | *Relocated hypocenter* | | | *Focal mechanism* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | Time | Long. | Lat. | FD (km) | CD (km) | Strike | Dip | Rake | $M_w$ | Ref. |
| 1977.12.18 | 16:47 | 77.4065 | 39.9236 | $22^d$ | $7^t$ | 74 | 51 | 79 | 5.8 | *1* |
| 1986.04.25 | 16:12 | 77.3404 | 40.1340 | $13^d$ | 15* | 283 | 60 | 125 | 5.4 | *4* |
| 1996.03.19 | 15:00 | 76.7353 | 40.0810 | $13^l$ | $34^t$ | 234 | 16 | 87 | 6.0 | *2* |
| 1996.03.20 | 00:14 | 76.8644 | 40.0562 | $17^l$ | $6^r$ | 268 | 20 | 76 | 4.5 | *3* |
| 1996.03.22 | 08:26 | 76.7983 | 40.0816 | $15^l$ | $6^r$ | 260 | 18 | 78 | 5.2 | *3* |
| 1996.04.02 | 02:28 | 77.5587 | 40.2328 | $10^l$ | $16^r$ | 242 | 59 | 128 | 4.1 | *3* |
| 1997.01.21 | 01:48 | 77.2050 | 39.6475 | $11^l$ | $12^t$ | 317 | 85 | 177 | 5.4 | *2* |
| 1997.01.29 | 08:20 | 76.9678 | 39.5923 | $12^l$ | 33* | 04 | 83 | 132 | 5.2 | *4* |
| 1997.03.01 | 06:04 | 76.9532 | 39.5288 | $14^l$ | $14^d$ | 180 | 80 | −173 | 5.6 | *2,4* |
| 1997.04.05 | 23:36 | 76.9622 | 39.5832 | $12^l$ | $18^t$ | 177 | 64 | −139 | 5.4 | *2* |
| 1997.04.06 | 04:36 | 77.0809 | 39.5694 | $12^l$ | $17^t$ | 246 | 41 | −74 | 5.8 | *2* |
| 1997.04.06 | 12:58 | 77.0324 | 39.6105 | $17^l$ | $13^t$ | 210 | 38 | −74 | 5.1 | *2* |
| 1997.04.11 | 05:34 | 77.0326 | 39.6023 | $15^n$ | $20^t$ | 226 | 42 | −79 | 6.0 | *2* |
| 1997.04.12 | 21:09 | 77.0039 | 39.5334 | $14^n$ | $16^t$ | 239 | 27 | −74 | 5.1 | *2* |
| 1997.04.15 | 18:19 | 77.0506 | 39.6461 | $14^n$ | $18^t$ | 177 | 64 | −139 | 5.7 | *2* |
| 1997.06.24 | 09:24 | 76.9562 | 39.5877 | $16^n$ | 34* | 345 | 72 | −167 | 5.1 | *4* |
| 1997.10.17 | 17:35 | 77.0875 | 39.5686 | $25^d$ | 33* | 177 | 64 | −139 | 5.3 | *4* |
| 1998.03.19 | 13:51 | 76.8048 | 40.1732 | $15^l$ | $15^d$ | 243 | 5 | 79 | 5.6 | *2,4* |
| 1998.08.02 | 04:40 | 77.0897 | 39.6817 | $10^d$ | $15^t$ | 173 | 40 | −140 | 5.5 | *2* |
| 1998.08.03 | 15:15 | 77.0905 | 39.6527 | $15^l$ | $29^r$ | 253 | 10 | 129 | 4.6 | *2* |
| 1998.08.27 | 09:03 | 77.4554 | 39.6437 | $16^l$ | $15^t$ | 57 | 80 | 1 | 6.3 | *2* |
| 1998.09.03 | 06:43 | 77.4162 | 39.6528 | $25^d$ | $10^r$ | 179 | 59 | 178 | 4.8 | *2* |
| 1998.10.31 | 16:09 | 77.2469 | 39.6081 | $19^l$ | $14^r$ | 152 | 74 | −164 | 4.6 | *2* |
| 2003.01.04 | 11:07 | 77.0350 | 39.6389 | $14^l$ | 33* | 245 | 73 | −20 | 5.2 | *4* |
| 2003.02.24 | 02:03 | 77.3157 | 39.5852 | $19^l$ | $5^t$ | 280 | 17 | 115 | 6.2 | *2* |
| 2003.02.24 | 21:18 | 77.2653 | 39.5663 | $12^l$ | 15* | 289 | 33 | 126 | 5.2 | *4* |
| 2003.02.25 | 03:52 | 77.4717 | 39.5385 | $8^l$ | 15* | 239 | 33 | 62 | 5.3 | *4* |
| 2003.03.12 | 04:47 | 77.5273 | 39.4969 | $8^l$ | $7^d$ | 245 | 33 | 73 | 5.7 | *2,4* |
| 2003.03.15 | 22:59 | 77.3459 | 39.5733 | $9^l$ | 15* | 330 | 57 | 178 | 5.0 | *4* |
| 2003.03.30 | 23:15 | 77.4315 | 39.5462 | $17^l$ | $10^t$ | 287 | 27 | 117 | 5.2 | *2* |
| 2003.05.04 | 15:44 | 77.2305 | 39.4369 | $9^l$ | 15* | 308 | 53 | 179 | 5.8 | *4* |
| 2003.06.04 | 16:28 | 77.6458 | 39.4665 | $10^l$ | $10^d$ | 274 | 54 | 92 | 5.2 | *2,4* |
| 2003.09.26 | 23:35 | 77.1664 | 40.2902 | $30^d$ | 15* | 290 | 13 | 58 | 5.3 | *4* |
| 2004.10.07 | 16:14 | 77.4633 | 40.2740 | $12^l$ | 17* | 245 | 14 | 72 | 4.8 | *4* |
| 2005.03.24 | 07:37 | 77.7478 | 39.9288 | $11^d$ | 30* | 187 | 35 | 32 | 4.8 | *4* |
| 2006.06.08 | 11:34 | 77.6951 | 40.4025 | $6^d$ | 30* | 290 | 35 | 113 | 4.8 | *4* |
| 2006.09.06 | 07:51 | 76.9389 | 40.3257 | $15^l$ | 32* | 258 | 37 | 91 | 4.7 | *4* |
| 2009.04.22 | 09:26 | 77.2583 | 40.1229 | $11^d$ | 16* | 264 | 50 | 124 | 5.0 | *4* |
| 2009.10.16 | 02:56 | 76.9545 | 39.9836 | $15^d$ | 19* | 284 | 32 | 116 | 5.0 | *4* |
| 2011.08.11 | 10:06 | 77.1232 | 39.9575 | $19^d$ | 12* | 272 | 42 | 109 | 5.6 | *4* |
| 2012.08.11 | 09:34 | 78.2335 | 40.0027 | $15^d$ | 12* | 255 | 43 | 84 | 5.3 | *4* |
| 2013.03.11 | 03:01 | 77.4916 | 40.1729 | $9^d$ | 12* | 210 | 11 | 50 | 5.2 | *4* |
| 2015.01.10 | 06:50 | 77.2838 | 40.1469 | $14^c$ | 15* | 227 | 17 | 57 | 5.1 | *4* |
| 2016.07.09 | 16:36 | 78.0578 | 40.0128 | $14^c$ | 12* | 240 | 32 | 53 | 4.8 | *4* |
| 2018.04.12 | 10:41 | 77.4068 | 40.4104 | $17^l$ | 22* | 231 | 36 | 50 | 4.9 | *4* |
| 2018.09.03 | 21:52 | 76.9341 | 39.5211 | $14^c$ | 15* | 317 | 89 | 178 | 5.5 | *4* |
| 2018.11.03 | 21:36 | 77.6323 | 40.2120 | $14^c$ | 12* | 225 | 12 | 63 | 4.9 | *4* |
| 2019.01.06 | 16:22 | 77.6093 | 39.9331 | $6^d$ | 12* | 238 | 50 | 79 | 4.9 | *4* |
| 2020.01.17 | 16:05 | 77.1167 | 39.8682 | $12^d$ | 21* | 261 | 86 | −178 | 5.3 | *4* |
| 2020.01.19 | 13:27 | 77.1161 | 39.8944 | $11^d$ | $7^i$ | 279 | 7 | 115 | 6.0 | *5* |
| 2020.01.19 | 14:23 | 77.4089 | 39.9236 | $14^c$ | 18* | 268 | 22 | 95 | 5.1 | *4* |
| 2020.02.21 | 15:39 | 77.4059 | 39.9232 | $14^c$ | 14* | 287 | 46 | 143 | 4.8 | *4* |

The thick Paleozoic sequence of mainly Upper Cambrian to Permian strata is exposed in a series of parallel anticlines (Xinjiang Bureau of Geology and Mineral Resources, 1992). The hanging wall cut-offs of the imbricate thrusts have been eroded away. This thrust system is interpreted as thin-skinned, with fault-propagation folds detached in Upper Cambrian limestones along a décollement at $\sim$6–10 km depth according to seismic reflection profiles and balanced geological cross-sections (Allen et al., 1999; Yin et al., 1998; Nishidai & Berry, 1990; Yang et al., 2010). The left-lateral Piqiang fault (Fig. 1) has developed perpendicular to the Kepingtag belt, dividing it into two (western and eastern) segments. Interpretations of satellite imagery and balanced cross-sections suggest that the thin-skinned imbricate thrusting and folding has accommodated crustal shortening strains of 20–28$\%$ between the main Tian Shan and Tarim block, equivalent to $\sim$35 km across the western segment and $\sim$22 km across the eastern segment (Allen et al., 1999; Yin et al., 1998).

## 2.2 Seismicity of the Kepingtag belt

Active crustal shortening and thickening of the southern Tian Shan is manifest in frequent reverse faulting earthquakes that cluster around the margins of the high topography with nodal planes oriented approximately parallel to the range (Ghose et al., 1998; Xu et al., 2006; Sloan et al., 2011). The Kepingtag belt and its adjacent foreland are amongst the most seismically-active parts of the Tian Shan, with thirty-six earthquakes of $M_w$ 5.0–6.3 since the late 1970s (Fig. 1b and Table 1). The 1902 $M_w$ 7.7 Atushi (Kashgar) earthquake, located $\sim$150 km west of our study area, hints that much larger earthquakes may be possible (Kulikova & Krüger, 2017). Within the Kepingtag belt, instrumental seismicity is concentrated west of the Piqiang fault and the available focal mechanisms indicate a predominance of thrust and reverse faulting. Assuming that northward-dipping nodal planes represent faulting, dip angles range from $\sim$5°–60° with an average of around 30°. Only a few of these events have reliable centroid depths from detailed waveform modelling, mostly in the range 6–16 km, consistent with faulting within the lower sedimentary cover and the underlying basement (Fan et al., 1994; Ghose et al., 1998; Sloan et al., 2011). Sloan et al. (2011) placed a single outlier event at 34 km depth, within the middle-to-lower crust, but noted that its relatively complex waveforms could potentially be explained by a compound (multi-event) source mechanism at a much shallower depth.

Seismicity in our study area peaked between 1997 and 1998 with thirteen earthquakes of $M_w$ 5.0–6.3 including the destructive January-October 1997 Jiashi earthquake swarm in the foreland south of the Kepingtag belt, which caused 21 fatalities (Zhang et al., 1999). This sequence involved a mix of strike-slip and normal faulting with well-resolved centroid depths of $\sim$12–20 km (Sloan et al., 2011), as well as some smaller, deeper earthquakes located by a temporary regional network but without reliable focal mechanisms (Xu et al., 2006). The mechanisms and depths are challenging to interpret but may reflect flexural rebound of the Tarim basin under loading from the Tian Shan (Sloan et al., 2011). On February 24 2003, a $M_w$ 6.2 earthquake struck the same area, resulting in 261 reported fatalities. In contrast with the 1997 swarm, the 2003 earthquake involved northward-dipping thrust faulting with a much shallower centroid depth of $\sim$5–7 km, interpreted to represent southward propagation of the Kepingtag belt into the Tarim basin (Sloan et al., 2011). It also produced an abundant aftershock sequence that was apparently concentrated in the middle crust between $\sim$15–25 km (Huang et al., 2006). Following the 2003 sequence, the study area entered a relatively quiescent period of seismic activity, with no earthquake of magnitude 6 or above until the January 19 2020 event.

The 2020 Jiashi sequence occurred within the southern part of the western Kepingtag belt. The $M_w$ 6.0 mainshock was preceded by two days of foreshock activity involving $\sim$N–S-oriented left-lateral strike-slip faulting (Yao et al., 2021a). The mainshock itself ruptured an $\sim$E–W-oriented thrust or reverse fault, though there is disagreement amongst available seismological and geodetic models on its geometry and depth, which will be discussed further in light of our own results in Section 4. The mainshock was followed by an energetic aftershock sequence that lasted at least three months (Ran et al., 2020; Yao et al., 2021a). *Pg* and *Sg* waves were recorded at fifteen seismic stations, including thirteen permanent stations at $\sim$30–170 km distance and two local stations $\sim$20 km SW and NW of the mainshock epicenter, which were deployed by the Xinjiang Earthquake Administration 4 and 18 hours after the mainshock, respectively. Using *Pg* and *Sg* arrival times, hypocenters of the mainshock and $\sim$300 $M_L \geq 1.8$ aftershocks up to February 11 were relocated using double-differencing (Ran et al., 2020; Yao et al., 2021a). Seismicity forms a 'T' shaped pattern in map view, with the mainshock located at the bottom of the 'T' and aftershocks extending $\sim$20 km northward to the junction of the 'T', and from there, $\sim$20 km east and west for a total length of $\sim$40 km, with the greatest concentration of events along the western branch (Ran et al., 2020; Yao et al., 2021a). These studies also show that the aftershocks are concentrated at depths of 10–20 km.

# 3 METHODS

## 3.1 InSAR measurements

We used InSAR to measure surface deformation in the January 19 2020 earthquake, and elastic dislocation modelling to estimate the fault geometry and slip distribution. The raw data are from the European Space Agency's C-band Sentinel-1A satellite, with wavelength $\sim$5.6 cm. Two ascending tracks (056A and 129A) and one descending track (034D) capture the Jiashi mainshock. Three, 12 day coseismic interferograms (January 11–23, January 16–28 and January 10-22 2020) were processed using the GAMMA software, and multilooked to 4 looks in range and 20 in azimuth for a $\sim$30 m pixel resolution. The topographic phase contribution was removed using the 30 m-resolution Shuttle Radar Topographic Mission Digital Elevation Model, which was also used to geocode the interferograms. The two ascending-track interferograms were unwrapped using the branch-cut algorithm (Goldstein et al., 1988) while the noisier, descending-track interferogram was unwrapped using the Minimum Cost Flow algorithm. Unwrapping errors were then manually corrected.

The interferograms exhibit excellent coherence, reflecting the dry desert conditions and sparse vegetation of the southwestern Tian Shan. Coseismic surface deformation is easily distinguished in all three interferograms as a double fringe ellipse elongated in an E-W orientation (Fig. 2a, d, g). The southern lobe is focused on the Kepingtag anticline and exhibits up to $\sim$7.5 cm of line-of-sight (LOS) displacement toward the satellite, and the northern lobe is centered along the Aozitag anticline and contains up to $\sim$5 cm of displacement away from the satellite (Figure 6a–c). The similarity of the fringe patterns in ascending and descending interferograms implies that the largest contribution to the observed LOS deformation is from uplift/subsidence rather than E/W lateral displacement, consistent with predominantly dip-slip faulting.

After downsampling the LOS displacements using a quadtree algorithm to concentrate sampling in regions with high phase variance (Jónsson et al., 2002), we employed a two-step inversion strategy to estimate the causative fault parameters. In the first step, we inverted the downsampled data using Powell's algorithm (Press et al., 1992) and Okada's expressions (Okada, 1992) to solve for the geometry of a rectangular, uniform slip model fault plane buried in an elastic half space with Lamé parameters $\lambda = \mu = 3.2 \times 10^{10}$ Pa, approximately consistent with regional upper crustal seismic velocities. The single descending interferogram was weighted equal to the two ascending interferograms in the inversion. The optimal model fault strike, dip, rake, length, top and bottom depths, and slip were determined using 500 Monte Carlo restarts with random starting parameters in order to avoid local misfit minima (e.g., Wright et al., 1999). Recognizing a strong trade-off between slip and fault width — which is common for buried thrust earthquakes — we obtained the initial fault geometry by fixing slip to 1.0 m. In the second step, we estimated the slip distribution by first extending the uniform slip model fault along strike and up- and down-dip and then dividing the fault plane into 1 km $\times$ 1 km sub-fault patches. We solved for the slip distribution using a finite difference Laplacian constraint to vary smoothing and chose a physically realistic solution using the 'L-criterion' (Wright et al., 2004; Funning et al., 2005). We manually removed a few outlier slip patches that lay several kilometers up-dip from the main slip distribution, which we considered spurious. The final distributed slip results were used to generate the forward model and residual interferograms shown in Fig. 2.

Given the structural complexity of the Kepingtag belt, we also investigated whether the Jiashi earthquake may have involved non-planar rupture geometries by inverting the InSAR displacements for two uniform slip model fault planes (e.g., Pousse-Beltran et al., 2020). We explored a range of listric and anti-listric configurations by matching the top depth of a deeper model fault to the bottom depth of a shallower model fault and varying each of their dip angles at 5° increments. However, none of the two-fault configurations that we tested produced a realistic geometry that improved upon the misfit of the simple, single-fault model. This leads us to strongly favour involvement of a single, planar fault.

### 3.2 Calibrated hypocenter relocations

We refined the hypocenter of the January 19 2020 mainshock by relocating and calibrating a cluster of regional seismicity using teleseismic, regional and local seismic phase arrival times. In addition to the mainshock, the cluster includes the principal foreshock ($m_b$ 4.3), two largest aftershocks ($m_b$ 5.1 and 5.0), and 148 well-recorded background events starting from 1977. Past multiple-event calibrated relocation studies in comparably instrumented areas elsewhere in Asia indicate that epicenters can be resolved to within $\sim$1–2 km and focal depths to within $\sim$5 km (Karasözen et al., 2019), improving substantially on the uncertainties of routine catalogs such as the USGS and GCMT (Engdahl et al., 2006). Juxtaposing calibrated epicenters with InSAR-derived slip models can distinguish bilateral from unilateral rupture propagation (e.g., Gaudreau et al., 2019; Pousse-Beltran et al., 2020) and help resolve ambiguities in subsurface fault geometry, which are otherwise commonplace for buried earthquakes (e.g., Roustaei et al., 2010; Copley et al., 2015; Elliott et al., 2015; Karasözen et al., 2018).

The cluster was relocated and calibrated in the *Mloc* program using an approach that is fast becoming routine (e.g., Walker et al., 2011; Elliott et al., 2015; Karasözen et al., 2016, 2018, 2019; Gaudreau et al., 2019; Pousse-Beltran et al., 2020; Bergman et al., submitted). *Mloc* utilizes the Hypocentroidal Decomposition method of separating the relocation into two distinct inverse problems reliant on customized phase arrival time data (Jordan & Sverdrup, 1981). In the first step, we solved for the relative locations of each hypocenter with respect to the reference hypocentroid, defined as the arithmetic mean of all individual event hypocenters within the cluster. This step relies principally upon teleseismic arrival times, of which there are an abundance for events included in the cluster. In the second step we calculated the absolute location of the hypocentroid and updated the absolute hypocenter coordinates of every event in the cluster. For this step we only used seismic phases recorded at local distances of up to 2°, for which there is excellent azimuthal coverage. Using local arrival times for this step is known as 'direct' calibration (e.g., Karasözen et al., 2016). For the best-recorded events, we estimated focal depths using local arrival times; for others, we relied upon teleseismic depth phases or simply fixed the focal depth to a representative cluster default of 14 km. We used a customized velocity model obtained during an earlier calibrated, multi-event relocation performed in the same study area (Bergman et al., submitted).

### 3.3 Teleseismic body waveform inversion

Finally, we used teleseismic body waveform modelling to provide additional constraints on the mainshock source depth and mechanism, complementing those from InSAR analysis. Centroid depths obtained in this way are particularly useful, since they can help clarify whether fault slip resolved by InSAR models occurred coseismically or through afterslip (Nissen et al., 2014).

We followed the approach of Heimann et al. (2018), and inverted vertical and transverse component data from stations between 3300 and 9900 km from the reported earthquake location. Waveforms were filtered between 0.01 and 1 Hz, and we used a window starting 15 seconds before, and ending 25 seconds after, the principle phase (*P* for vertical component waveforms, *S* for transverse component waveforms). Observed data and synthetics were aligned using cross correlation. The Bayesian approach outlined in Heimann et al. (2018) allows for the full sampling of the parameter space available in source depth, latitude, longitude, magnitude, and mechanism. The source-time function is constrained to be a variable-duration half-sinusoid — appropriate for an earthquake of this size, and for the frequencies used in our inversions.

## 4 RESULTS

Our best-fitting InSAR uniform slip model fault strikes 279°, dips 7° N, has a slight right-lateral component (rake 115°), and is $\sim$22 km long by $\sim$2 km wide, centered at 7 km depth (Tab. 2). To further test model sensitivity to centroid depth, we ran the inversion by prescribing different (fixed) top and bottom depths while allowing other parameters to vary freely. We also undertook similar tests of model sensitivity to dipping angle. There is a fairly steep increase in misfit at fault center depths shallower or deeper than the minimum misfit value of 7 km (Fig. 3a). For the equivalent dip sensitivity test, we find low misfits for dip angles of 5–10°, but abrupt increases in root mean square error outside of this range.

Compared to the uniform slip model, our preferred distributed slip model is longer at ∼37 km and wider at ∼9 km, but remains centered at ∼7 km depth (Fig. 4). The slip distribution is characteristically narrow, with an aspect ratio (length to width) of around 4. The peak slip is ∼0.5 m and the model moment is $\sim 1.75 \times 10^{18}$ N. The resultant forward model interferogram matches the observed surface deformation closely, with less than one residual fringe and a root mean square error of ∼0.25 m (Fig. 2c, f, i), which is substantially lower than that of the uniform slip model (∼0.35 m).

The fault plane we modelled using InSAR data has a similar strike, dip and rake to the USGS body-wave moment tensor solution, with differences possibly reflecting common trade-offs between strike and rake (Table 2). Our distributed slip model has a slightly larger moment than the three available seismological catalogue solutions. The InSAR data capture the surface deformation accumulated over a period from one week before to one week after the mainshock, and thus it is impossible to separate definitively the mainshock coseismic slip from postseismic motion such as aseismic creep. Therefore, we suggest that the larger moment of our slip model reflects contribution of the postseismic afterslip to the surface deformation.

Three other InSAR-derived fault models are also available for comparison (Tab. 2). Our model is closest to the single fault solution of Yu et al. (2020); the two models agree within 4° in strike, dip and rake, and within 1 km in centroid depth. Their preferred, two-fault model is strongly listric, with slip apportioned between a deep, gentle (2°) décollement and a much steeper (52°) ramp. However, we prefer the single-fault solution, as the two-fault models we tested using different configurations of listric and antilistric faults could not yield smaller misfits. Our model is ∼2 km deeper and significantly shorter and narrower than a uniform slip model by Yao et al. (2021b). However, they do not provide model or residual interferograms, so there is no easy way to assess the accuracy of their model.

Our relocated mainshock hypocenter lies beneath the northern limb of Kepingtag anticline, which is located ∼6.6 km NNW from one inferred by Ran et al. (2020) using local data. However, our epicenter is somewhat closer to the InSAR-derived slip distribution patch, lying at its far western end. Both our model and Ran et al. (2020)'s show that the Jiashi earthquake is clearly strongly unilateral, rupturing from west to east. Our relocated epicenter of the January 17, 2020 $m_b$ 4.3 foreshock lies $\sim$3 km SE from the mainshock, and the two largest aftershocks ($m_b$ 5.1 and 5.0) lie near the eastern end of the mainshock model slip patch (Fig. 1c).

We show the results of our seismological inversions in Fig. 5 and synthetic waveforms for all stations used in the inversion in the supplementary material (Fig. S1–S4). A probability density function (PDF) of centroid depth results from an inversion with all parameters free shows both the mean and the best-fit solution at just under 10 km (Fig. 5a). Using teleseismic data offers good constraints on the mechanism only near the center of the focal sphere, where the pierce-points of teleseismic waves cluster. As such, the mechanism, and particularly the shallowly dipping nodal plane are poorly constrained (inset mechanism, Fig. 5a). Consequently, we repeated the inversion using double couple nodal planes fixed to match the InSAR-determined fault plane (Fig. 5b). This pushes the PDF slightly deeper, with a mean depth at 11 km, but with a best-fit solution still at 10 km, and makes only a marginal difference to the overall misfit values. We also show the PDF for the seismologically-determined magnitude in Fig. 5c, which matches well with the inferred magnitude of the geodetic signal.

In order to illustrate the constraints that the teleseismic data offer on the centroid depth, we show a set of six example waveforms (three vertical component, three transverse component) and best-fit synthetics calculated using 3 fixed centroid depths in Fig. 5d. The middle row shows waveforms calculated at 10 km centroid depth, which is the best fit seismological solution, while the upper row shows waveforms with the depth fixed to match the geodetic results at 7 km, and the lower row shows waveforms with the depth fixed to match the centre of the regionally-determine aftershock distribution at 15 km. We discuss these waveform misfits further in the following section.

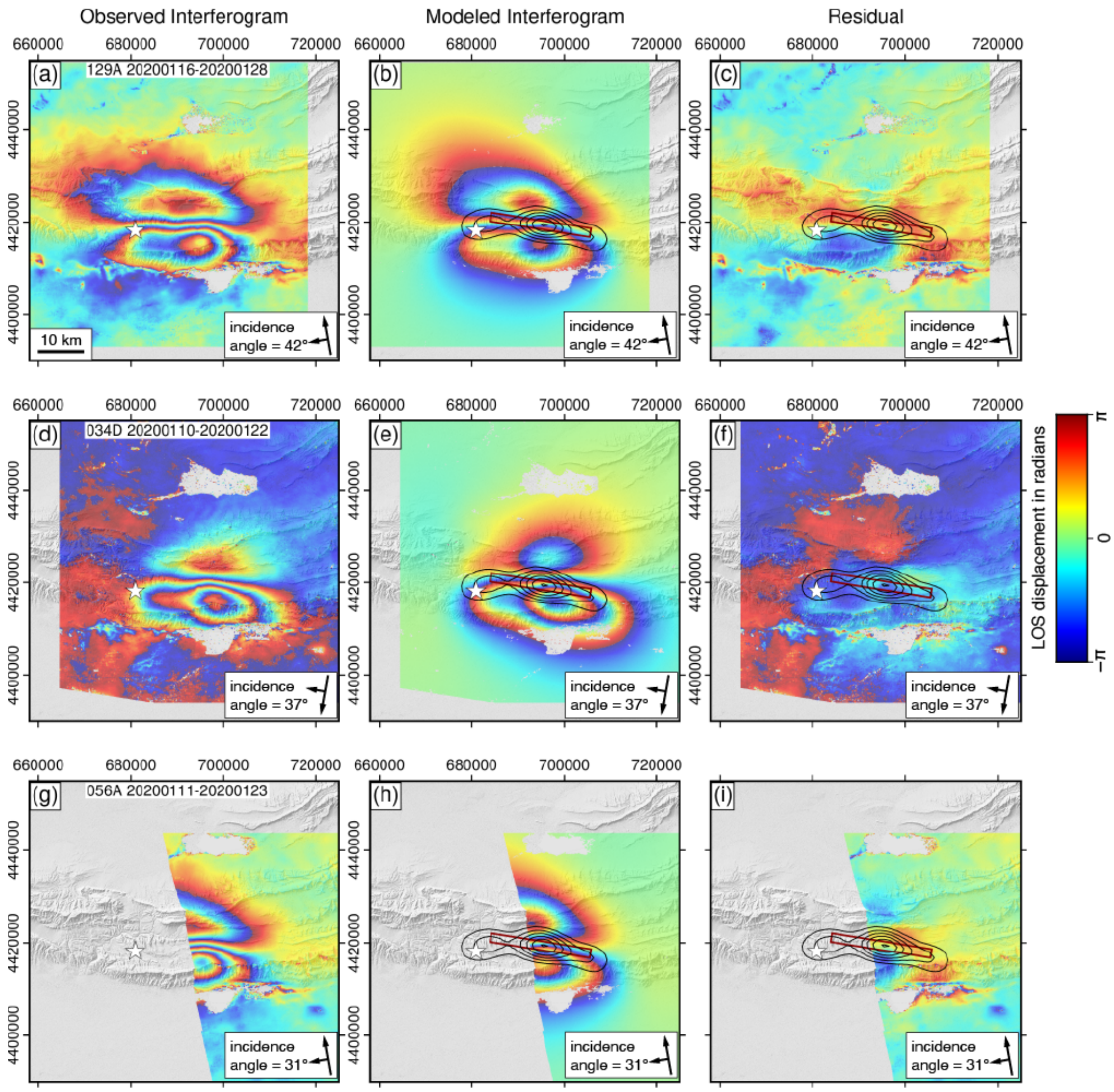


**Figure 2.** (Left column) Observed, (center) distributed slip model and (right) residual interferograms of the 2020 Jiashi mainshock rupture. Modelling was performed using unwrapped LOS displacements, but the interferograms are re-wrapped to show more clearly the shape of the deformation field. Color cycles of blue through yellow to red indicate motion away from the satellite and one color cycle ($2\pi$ radians) represents a half radar wavelength (2.77 cm) of LOS displacement. The satellite track azimuths and LOS direction with local angle of incidence are indicated by the longer and shorter black arrows, respectively. The white star indicates the relocated mainshock epicenter. In the central and right-hand panels, ten centimeter model slip contours are shown in black and the outline of the uniform slip model fault plane is marked in dark red.

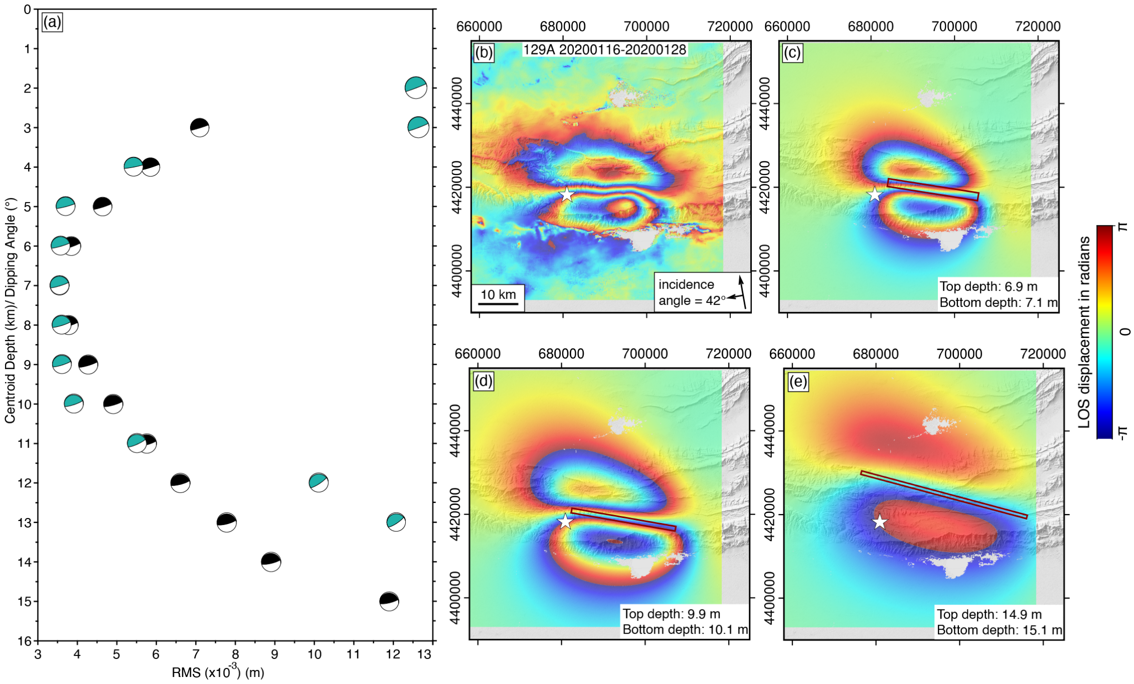


**Figure 3.** (a) Fault center depth (black) and fault dip (green) sensitivity tests of our InSAR uniform slip fault models for the 2020 Jiashi mainshock. Each focal mechanism shows the minimum-misfit model solution for a fixed center depth (black) or a fixed dip angle (green), with all other parameters kept free in each inversion. The $x$-axis is root mean square error (RMS) in meters; the $y$ axis shows 1 km increments of fixed center depth and 1° increments of fixed dip. (b) Observed ascending track interferogram (same as in Fig. 2a). (c) Preferred uniform slip model interferogram, with its (free) center depth of 7 km. (d) A forward model interferogram with center depth fixed to 10 km. The forward model used the same uniform slip parameters as in (c) except for the top and bottom depth and the surface projection coordinates. (e) Same as (d) but with a centroid depth of 15 km.

## 5 DISCUSSION

### 5.1 Depth discrepancy between the 2020 Jiashi mainshock and its aftershocks

Our InSAR-derived model suggests that the Jiashi mainshock ruptured along the décollement at the base of the sedimentary cover, with a centroid depth of ∼7 km. From the high-quality locally-recorded and double-difference relocated aftershock data, aftershocks cluster along E–W and NNW–SSE trends, with the former matching the ∼40 km length and orientation of our slip

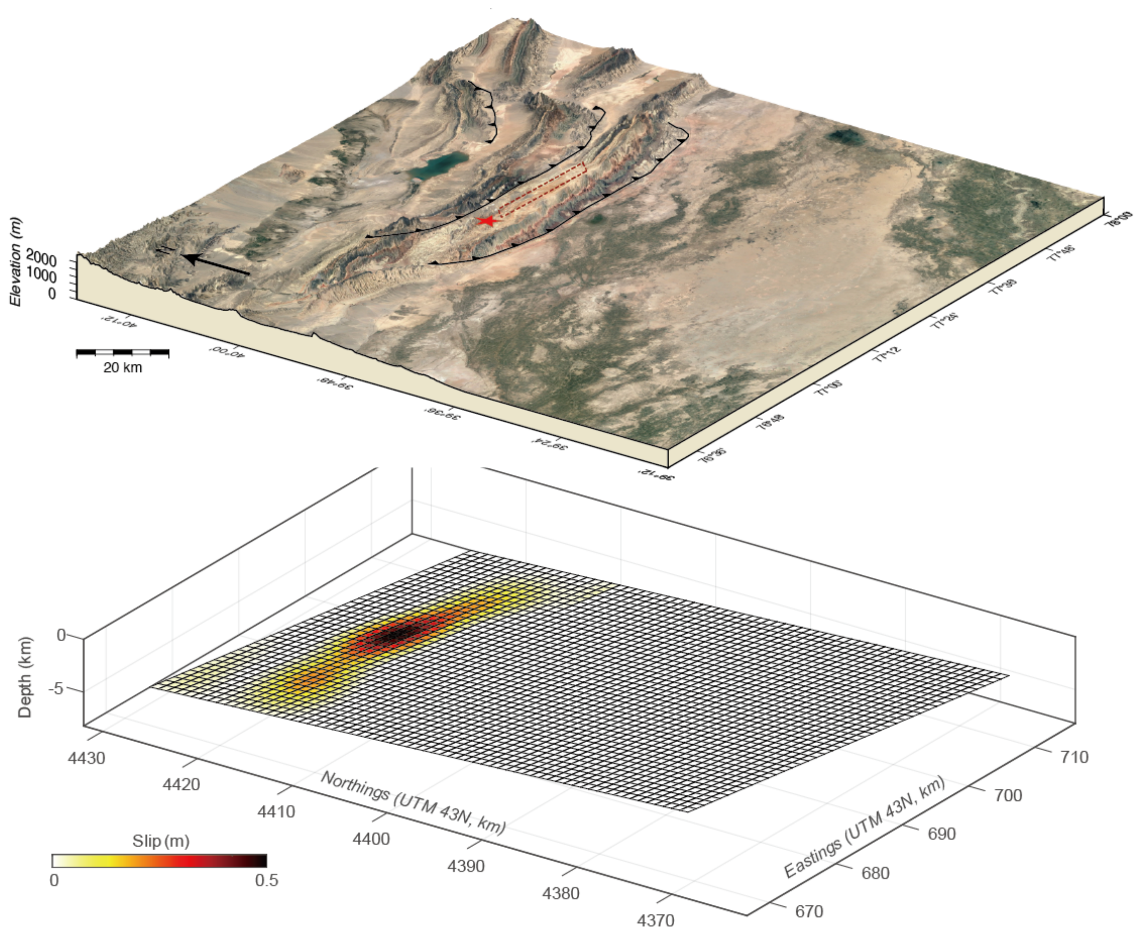


**Figure 4.** (Top) Google Earth perspective view of the Kepingtag belt and its adjacent foreland. The dark red dashed box marks the outline of our uniform slip model fault plane for the 2020 Jiashi earthquake. The red star is the relocated epicenter near the western end of the fault. (Bottom) Co-located perspective view of the coseismic slip distribution. Significant slip occurs over the depth range 6.5–7.4 km.

model (Ran et al., 2020; Yao et al., 2021a). However, locally-recorded aftershocks concentrate at 10–20 km depth, well below the depth of mainshock slip resolved by InSAR inversion. We consider two possible explanations for this apparent discrepancy.

The first possible explanation is that the surface deformation captured with InSAR may reflect aseismic afterslip along the décollement, above an earthquake buried within the underlying basement and itself invisible to InSAR. We tested this possibility by forward modelling the interferograms based upon a $M_w$ 6.0 thrust earthquake with the same geometry as our preferred

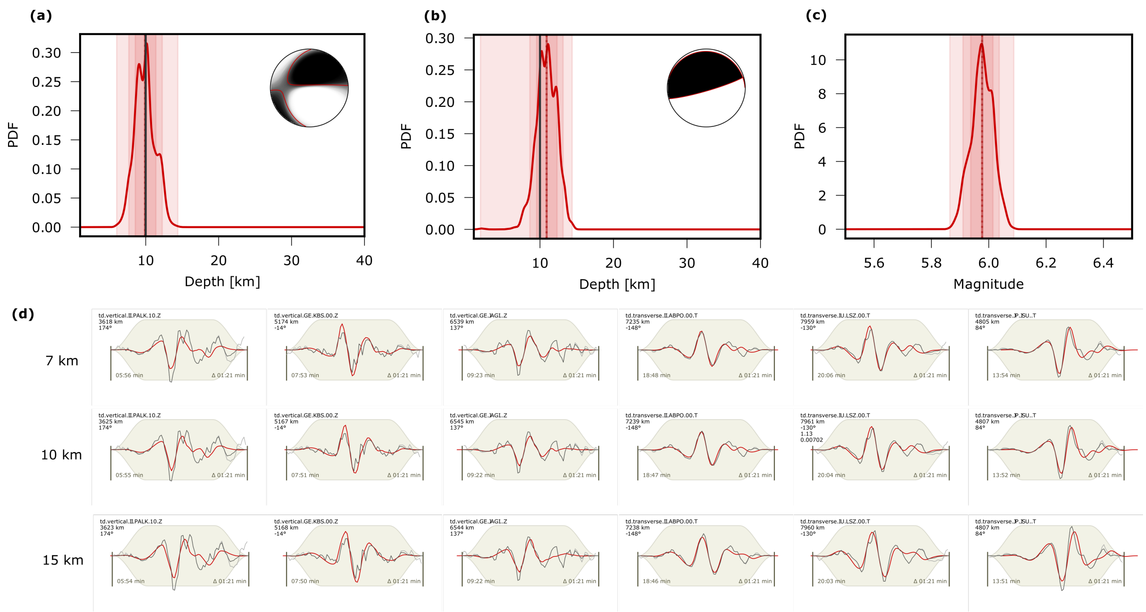


**Figure 5.** Seismological processing results for the 2020 Jiashi mainshock. (a) Probability-density function for depth, for an inversion with all parameters free. Inset mechanism shows the mechanism probability density function (greys) and the best-fit solution (red). (b) Probability-density function for depth, for an inversion with the mechanism constrained to be a double couple matching the InSAR-derived fault plane. (c) Probability-density function for moment, for an inversion with the mechanism constrained to match the InSAR-derived fault plane. (d) Example waveforms for 6 stations (three vertical component, three transverse component). Black traces show the observed data, red line shows the best-fitting inversion result. Text on each waveform indicates the station and component, epicentral distance, and azimuth. Each row of waveforms show synthetics calculated at 7, 10, and 15 km respectively, as discussed in the text.

uniform slip model fault but centered at depths of 10 km and 15 km, more consistent with the aftershock seismicity (Fig. 3c, d). These forward model interferograms match poorly with the observed InSAR data, with noticeably more far-field deformation and a broader spacing of fringes between the southern and northern lobes. However, the fact that deformation remains clearly distinguishable leads us to rule out the possibility that coseismic slip is too deep to be resolved with InSAR.

The second possible explanation is that the InSAR captures mainshock slip but that well-located aftershocks are vertically separated from the mainshock, faulting within the underly-

**Table 2.** Source parameters of the 2020 Jiashi mainshock inferred from our model and other sources. The longitude and latitude listed for our InSAR-derived models (first two rows) represent the surface projection of the model slip plane; our relocated epicenter is 77.117° E and 39.894° N. Where three depths are given, they represent the top, middle and bottom depth of the slip plane; where only one is given, it represents the centroid. L and W are length and width, respectively. Yu et al. (2020) prefer their listric, two fault model with a deeper, flatter segment fixed at 2° dip and a shallower, steeper ramp at 52°. Yao et al. (2021b) used uniform slip of 0.32 m in their InSAR-derived model, which may account for their much larger model fault plane.

| Source | Long. | Lat. | Strike | Dip | Rake | Depth (km) | L/W (km) | Moment (Nm) | $M_w$ |
|---|---|---|---|---|---|---|---|---|---|
| This study, uniform slip | 77.279° | 39.902° | 279° | 7° | 115° | 7.0/7.1/7.2 | 22/2 | $1.31 \times 10^{18}$ | 6.0 |
| This study, distributed slip | 77.165° | 39.416° | 279° | 7° | 115° | 6.3/7.0/7.6 | 37/9 | $1.75\times 10^{18}$ | 6.0 |
| CGMT | 77.19° | 39.80° | 196° | 38° | 31° | 11 | – | $1.39 \times 10^{18}$ | 6.0 |
| USGS body-wave | 77.11° | 39.84° | 262° | 9° | 105° | 4 | – | $1.493 \times 10^{18}$ | 6.1 |
| USGS $W$-phase | 77.11° | 39.84° | 221° | 20° | 72° | 19.5 | – | $1.387 \times 10^{18}$ | 6.0 |
| Yu et al. (2020), 1 fault | 77.30° | 39.91° | 275° | 9° | 111° | 6.3 | – | – | 6.1 |
| Yu et al. (2020), 2 faults | 77.30° | 39.90° | 275° | 2°/52° | 111° | 4.15 | – | – | 6.1 |
| Yao et al. (2020) | 77.68° | 39.31° | 269° | 20° | 92° | 4/5/6 | 58/30 | $2.29 \times 10^{18}$ | 6.2 |

ing basement. The absence of shallow aftershocks might reflect that the sediments above the décollement are velocity strengthening (Karasözen et al., 2016), or that the seismic network is insensitive to shallow events due to its average station spacing of ~30 km. Local seismic networks are able to constrain the focal depth most accurately only if *Pg* and *Sg* phases are recorded at epicentral distances of less than ~1–2 times of focal depths and the average station spacing is also less than ~1–2 times of focal depths (Gomberg et al., 1990). Therefore, the apparent absence of shallow events may be an artefact, as the stations with average spacing of ~30 km cannot record aftershocks shallower than 15 km depth.

We prefer the second explanation as the results from teleseismic waveform inversion help us to reinforce that the geodetically-imaged signal is indeed coseismic deformation. The waveform misfit differences between depths of 10 km and 7 km are minimal (Fig. 5d). However, synthetics are notably too broad at all six of the stations shown at depth of 15 km. Due to the cross-correlation based alignment, synthetics are typically aligned on the dominant peak to minimise misfit. However, at 15 km depth, this leads to the peaks to either side being too far out from the main peak due to the increase separation between direct and depth phases. Thus, we conclude that the seismological data are consistent with the deformation signal detected using InSAR, but are notably shallower than the aftershocks located using regional seismology.

In addition, mainshock–aftershock depth discrepancies are not uncommon and several other earthquake sequences also exhibit similar characteristics. The 2000 $M_w$ 6.6 Torrori (Japan), 2003 $M_w$ 6.6 Bam (Iran), 2008 $M_w$ 7.9 Wenchuan (China), 2009 $M_w$ 5.9 Karonga (Malawi), 2011 $M_w$ 5.9 Simav (Turkey), and 2014 $M_w$ 6.1 South Napa (California) earthquakes all exhibited shallower mainshock slip, resolved mostly using geodesy, with deeper aftershock distributions, resolved using seismology (Semmane et al., 2005; Jackson et al., 2006; Tong et al., 2010; Wei et al., 2015; Karasözen et al., 2016; Gaherty et al., 2019). Similar patterns were also observed in $M_w$ ∼6 earthquakes and aftershock sequences at Qeshm (2005) and Fin (2006) in the Zagros Simply Folded Belt, Iran (Nissen et al., 2010; Roustaei et al., 2010). These are especially analogous to the Jiashi sequence, as the Zagros mainshocks were centered within a thick sedimentary cover, with aftershock microseismicity vertically separated within the underlying basement (Nissen et al., 2014). Finally, we recollect that the February 24, 2003 $M_w$6.2 Jiashi earthquake in the foreland basin south of the Kepingtag was centered at ∼5–7 km depth, but exhibited aftershocks at ∼15–25 km depth (Huang et al., 2006; Sloan et al., 2011).

## 5.2 Structural interpretation of the 2020 Jiashi rupture

Coseismic uplift in the 2020 $M_w$ 6.0 Jiashi earthquake resolved by InSAR is centered along the back limb of the Kepingtag anticline (Fig. 6a–d). Seismic reflection profiles and balanced geological cross-sections depict this as a fault-propagation fold, with Paleozoic-Mesozoic sediments thrust over Cenozoic strata along the moderately northward-dipping Kepingtag fault, which branches off a décollement with an estimated depth of ∼5–10 km (Yin et al., 1998; Allen et al., 1999; Yang et al., 2010, 2002). Projecting our slip model onto a modified geological cross-section suggests that the 2020 earthquake ruptured the décollement where it intersects with the base of the Kepingtag thrust fault (Fig. 6e).

A striking feature of our distributed slip model is its elongate shape, with a width-to-length ratio of less than 1/4 (Figure 4). We interpret that the earthquake was able to propagate readily along strike, but was prevented from doing so up- and down-dip. We consider two potential causes of this pattern. One possibility is that the stratigraphic configuration could have determined where slip was able to propagate, with rupture restricted to competent rocks such as the lowermost Cambrian limestone. A similar explanation was proposed by Elliott et al. (2015) for the elongate slip distribution of the 2013 $M_w$ 6.2 Khaki-Shonbe earthquake in the Zagros fold-and-thrust belt, where Infracambrian Hormuz evaporites and Cretaceous Kazhdumi mudstones were inferred to have controlled the bottom and top of the rupture, respectively. Another possible mechanism could be due to structural complexities in the fault geometry. This was discussed by Elliott et al. (2011) for the 2008 and 2009 Qaidam $M_w$ 6.3 earthquakes, whose vertical segregation resulted from disruption of the rupture plane by a cross-cutting, conjugate reverse fault. In the 2020 Jiashi event, we suggest that the abrupt change in dip angle between the sub-horizontal décollement and the much steeper Kepingtag fault may have provided a barrier to rupture. Our testing of listric fault geometries is in good agreement with the inference that there was minimal slip on the steeper fault. Although the current data does not allow us to distinguish between the two mechanisms, there is a clear structural or lithological control on the extent of coseismic slip during the mainshock.

### 5.3 Regional distribution of seismicity and seismic hazard

The Pamir and Tian Shan jointly accommodate a crustal shortening of 20–25 mm/yr, nearly half of the total India-Eurasia convergence rate (Abdrakhmatov et al., 1996; Zubovich et al., 2010). The southwestern margin of the Tian Shan is characterized by frequent seismicity, mostly with thrust faulting and strike-slip mechanisms. Here, we use our own calibrated earthquake relocations together with previous waveform modelling studies to assess the finer-scale distribution of seismicity across this region.

From the calibrated earthquake relocations, it is apparent that seismicity is not concentrated along the frontal Kepingtag belt, but is distributed throughout the fold-and-thrust belt as well as the adjacent foreland to the south. The shallow events occur to the north of the frontal Kepingtag anticline as well as in the foreland to the south. This pattern indicates that the stacking of thrust

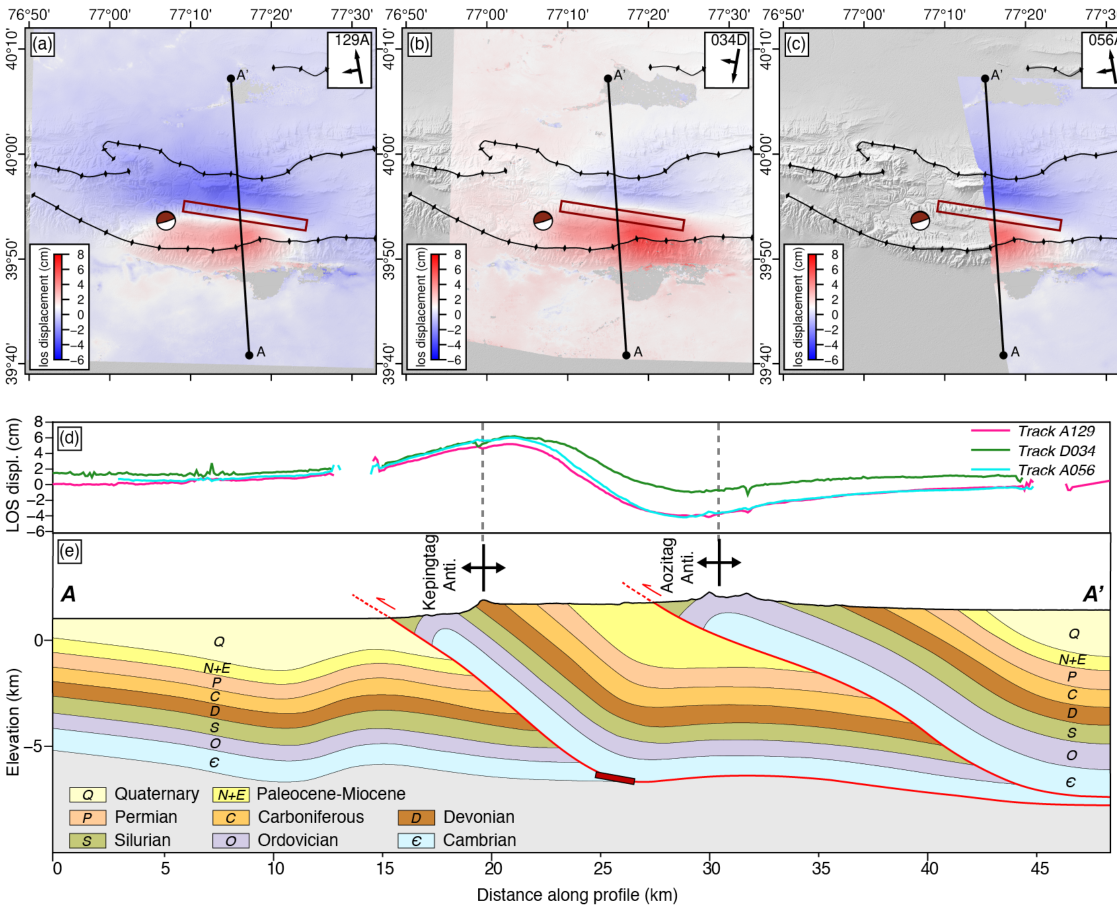


**Figure 6.** Coseismic LOS displacements in the 2020 Jiashi earthquake from unwrapped interferograms on tracks (a) 129A, (b) 034D and (c) 056A. Black lines with ticks show the traces of the Aozitang (north) and Kepingtag (south) fold axes. The dark red rectangle is the uniform slip model fault plane, centered at ∼7 km depth. (d) LOS displacement profiles (track 129A in pink, 034D in green, and 056A in cyan) along profile A-A' in (a), (b) and (c). Maximum LOS displacements are ∼7.5 cm toward the satellite and ∼4 cm away from the satellite. (e) Geological cross-section along the profile A-A', interpreted from seismic reflection profiles (Yang et al., 2010). The surface topography is extracted from the 30 m resolution SRTM DEM. The dark red rectangle indicates the uniform slip model fault plane.

sheets occurs out-of-sequence and the propagation of thrusting into the foreland is not a continuous process, in agreement with geomorphological and geochronological data (Yang et al., 2006). This suggests that seismic hazard is high across the region, rather than being focused along the range front as it is in some other fold-and-thrust belts (e.g., Nissen et al., 2010).

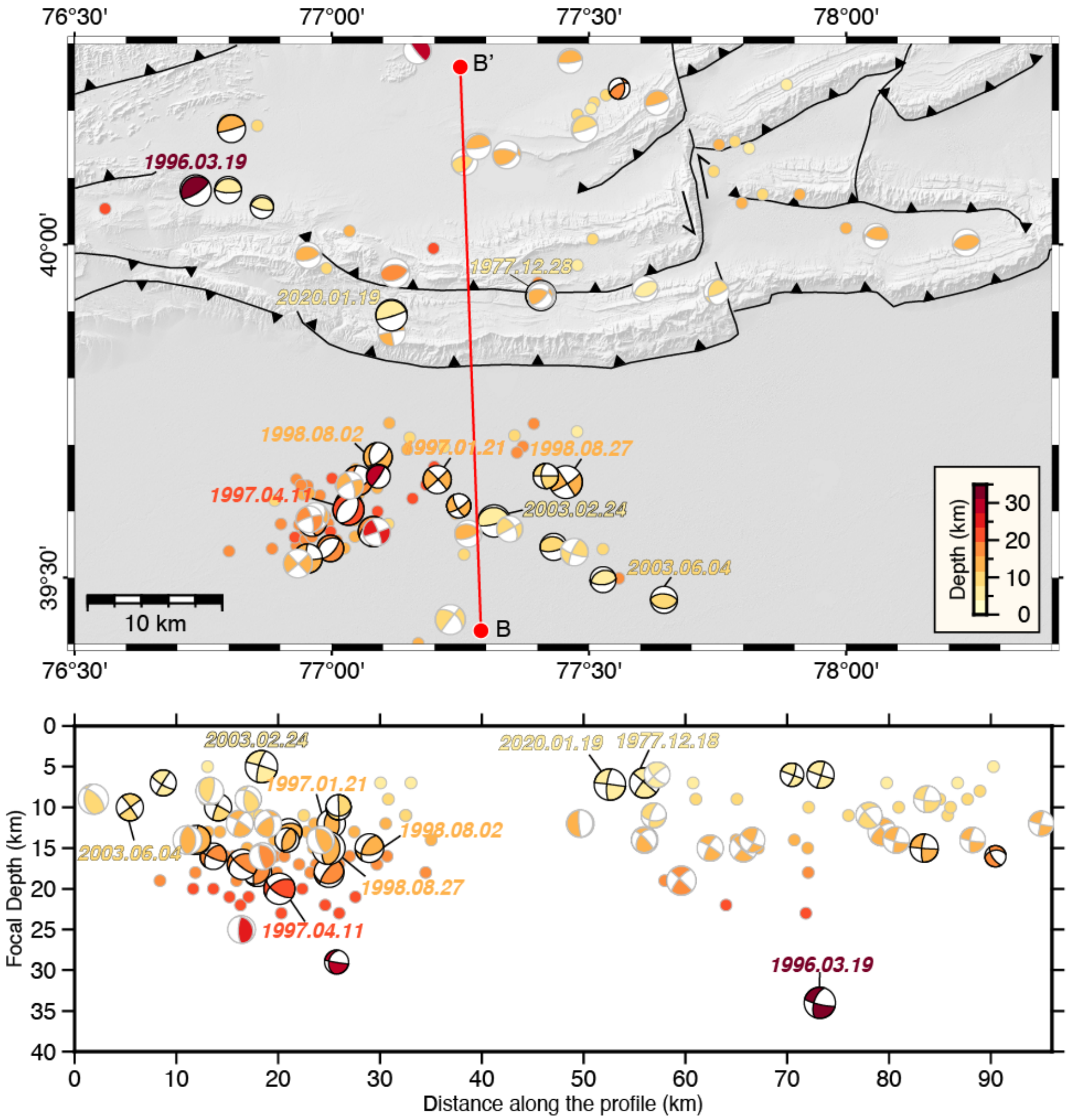


**Figure 7.** Calibrated relocated earthquakes from 1977–2020 in the Jiashi area, coloured according to the best available estimate of depth. Focal mechanisms determined by teleseismic and regional waveform modelling, including some from the GCMT catalogue. The depths of focal mechanisms with black outlines are determined by teleseismic and regional waveform modelling and depth phases, while those with grey outlines are our own calibrated focal depths (see Table 2 for full details). Other moderate relocated earthquakes without focal mechanisms are shown as dots.

Moreover, the seismic hazard in the Kepingtag region is not only restricted to faulting along the décollement but also within the folded and faulted cover rocks. Reliable earthquake centroid and focal depths — from teleseismic or regional waveform modelling (Fan et al., 1994; Ghose et al., 1998; Sloan et al., 2011) and our own calibrated hypocentral relocations — are concentrated at depths shallower than 25 km, except for two isolated events at 29–35 km (Fig. 7). Within the Kepingtag fold-and-thrust belt, most of the reliable centroid depths are greater than 10 km, indicating faulting within the basement below the décollement. Though usually depicted as a 'thin-skinned' fold-and-thrust belt, the Kepingtag basement clearly accommodates shortening by reverse faulting, and should therefore be considered as an important source of seismic hazard.

## 6 CONCLUSION

We use InSAR data to characterize the coseismic surface deformation and model the fault geometry and slip distribution of the January 19 2020 $M_w$ 6.0 Jiashi earthquake. Modelled coseismic uplift is centered on the back limb of the Kepingtag anticline, consistent with previous structural models that depict this as a fault-propagation fold. Our best-fit model fault plane dips $\sim 7°$ northward at depth of $\sim 7$ km, placing it on or close to the mapped décollement at the base of the folded sedimentary cover. This depth is consistent with teleseismic body-waveforms, confirming that the slip modelled with InSAR occurred coseismically. Published seismological studies show that aftershocks cluster within underlying basement rocks at $\sim 10$–20 km depth, and we suggest that the absence of shallower aftershocks may reflect that sedimentary layers above the décollement are velocity strengthening. Another noticeable feature of the mainshock is its small ratio (1/4) of rupture width to length, which likely reflects structural and/or lithological controls on slip propagation. Specifically, we suggest that slip was prevented from advancing up-dip by the abrupt change of dip angle between the sub-horizontal décollement and the much steeper Kepingtag thrust. Calibrated earthquake relocations indicate diffuse seismicity across the Kepingtag belt and its adjacent foreland and though the commonly described 'thin-skinned' fold-and-thrust belt; most of the reliable earthquake depths are consistent with locations of faulting in the basement.

## ACKNOWLEDGMENTS

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## Data availability

Interferograms were constructed using Copernicus Sentinel-1 data (2020) available from https://scihub.coperni and processed in GAMMA software (https://www.gamma-rs.ch/). InSAR modelling codes are available from E. N. upon reasonable request. Earthquakes were relocated using $Mloc$ software (https://seismo.com/mloc/), using starting location parameters from the International Seismological Centre Bulletin (http://www.isc.ac.uk/iscbulletin/). Full calibrated relocation results will be posted to the USGS ScienceBase website for the Global Catalog of Calibrated Earthquake Locations (GCCEL) (https://www.sciencebase.gov/catalog/item/ 59fb91fde4b0531197b16ac7). We also used focal mechanism data from the Global Centroid Moment Tensor project (https://www.globalcmt.org/) Several of the figures in the paper were plotted using Generic Mapping Tools (https://www.generic-mapping-tools.org/).

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