Introduction

JGS
Journal of the Geological Society

https://doi.org/10.1144/jgs2022-125 | Vol. 180 | 2022 | jgs2022-125

Fold-and-thrust belts and associated basins: a perspective on their structure, sedimentation, and dynamics

Feng Cheng[1]*, Andrew V. Zuza[2], Yiduo Liu[3] and Kurt Sundell[4]

[1] Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, School of Earth and Space Sciences, Peking University, Beijing 100871, China
[2] Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557, USA
[3] Department of Earth and Atmospheric Sciences, University of Houston, TX 77204, USA
[4] Department of Geosciences, Idaho State University, Pocatello, ID 83209-8072, USA
FC, 0000-0001-8734-6183
* Correspondence: cfcf.chengfeng@gmail.com

Abstract: Fold-and-thrust belts are structural features that accommodate upper-crustal shortening by the growth of a series of thrust faults and folds. Recent studies show that a better understanding of the structure and sedimentation styles of fold-and-thrust belts and their associated basins can provide crucial insights for improved interpretations of the evolution of ancient and modern convergent margins and the mechanisms of intracontinental deformation. To achieve a more comprehensive understanding of the development of contractional orogenic belts, this thematic collection gathers contributions that explore different types of fold-and-thrust belts at various scales around the world, via different approaches including theory development, structural and stratigraphic observations from the field, geophysical analyses, and numerical modelling. Case studies include the northern margin of the Tibetan plateau and Pamir region, the Timanian and Caledonian orogenies in northern Norway, orogenic belts in western Laurentia, and the Andes of western South America. These studies reemphasize the importance of integrating broad datasets when documenting the distribution, geometry, and kinematics of structures in fold-and-thrust belts and their associated basins, including field-based structural observations, provenance, low-temperature thermochronologic, geomorphologic, and subsurface data, and analog and numerical models. This thematic collection aims to encourage further efforts for comparative studies of the fold-and-thrust belts around the world and proposes interdisciplinary research to address outstanding questions in the study of contractional orogens.

Thematic collection: This article is part of the Fold-and-thrust belts collection available at: https://www.lyellcollection.org/topic/collections/fold-and-thrust-belts-and-associated-basins

Received 16 August 2022; **revised** 22 September 2022; **accepted** 23 September 2022

Fold-thrust belts are structural features that accommodate upper-crustal shortening by the growth of a series of thrusts and folds (Chapple 1978; Davis *et al.* 1983; Dahlen 1990; Suppe and Medwedeff 1990; DeCelles 2011; Chapman and DeCelles 2015). The development of fold-and-thrust belts and their associated basins (e.g. foreland basins) provide important constraints on the physical laws that govern orogenic evolution and crustal dynamics over multiple time scales (Tucker and Slingerland 1996; Horton and DeCelles 2001; DeCelles 2011; Tavani *et al.* 2015). Benefiting from the improvement in subsurface imaging and widespread petroleum exploration, fold-and-thrust-belt theory has significantly advanced since the second half of the twentieth century. New field datasets coupled with progress in kinematic and dynamic modelling are converging to provide more robust interpretations on the geometry, kinematics, and surface processes of fold-thrust belts. This thematic collection mainly collates papers presenting results from recent studies on the evolution of fold-and-thrust belts across the globe.

Integration of field structural observation and subsurface data (e.g. seismic profiles, well data) is an effective way to document the distribution, geometry, and kinematics of structures in a fold-and-thrust belt system (Namson and Davis 1988; Allen and Allen 2013). This approach has been widely applied to fold-and-thrust belt systems that developed in the petroliferous basins where hydrocarbon exploration generates abundant seismic reflections. To document the geometry of structures in the Varanger Peninsula, northern Norway, Gabrielsen Roy *et al.* (2022) combined field observation records with high-resolution multibeam bathymetric data from outer Varangerfjorden. Integration of previously published structural data and new observations allowed them to reveal the double-folding and thrust-front geometries associated with the Timanian and Caledonian structural history of the Varanger Peninsula. Similarly, integrating the results of satellite imagery analysis, field mapping of strike-slip faults, and subsurface seismic reflection interpretation across the Qilian Shan mountain belt, Cheng *et al.* (2021) examined the Cenozoic structural framework of the Qilian Shan fold-and-thrust belt, which marks the northeastern margin of the Tibetan plateau (Cheng *et al.* 2019*b*). Cheng *et al.* (2021) propose that the Cenozoic deformation in northern Tibet is compatible with the west–east crustal stretching, non-rigid off-fault deformation, and broad clockwise rotation and bookshelf faulting. This deformation interference pattern in northern Tibet elucidates how plate convergence is accommodated by intracontinental strike-slip faulting and block rotation within a fold-and-thrust belt.

Exploration of petroliferous basins and the acquisition of new high-quality seismic reflection profiles allows for updated quantitative constraints on the geometry and kinematic growth history of fold-thrust belts based on balanced-cross sections (Roure *et al.* 1989; Woodward *et al.* 1989; Allen and Allen 2013). Due to the early Cenozoic initiation of convergence between India and Eurasia, a number of fold-and-thrust belts were formed in the Circum-Tibetan Plateau Basin and Orogen System (Jia *et al.* 2013). To explore the mechanism that drove the intracontinental deformation in this region, Chen *et al.* (2022) present three balanced cross sections across the SW Tarim−West Kunlun orogen, NW Tarim

−SW Tian Shan, and southern Jungger−Northern Tian Shan. By integrating a comprehensive structural analysis of these transects with existing thermochronology and geophysical datasets, Chen *et al.* (2022) propose a two-phase intracontinental deformation mode, with initial Paleogene deformation confined to the pre-existing weak zones and the Miocene stage of deformation confined to the fold-and-thrust belts.

In addition to field observations and subsurface data interpretation, assessment of the geomorphic indices and thermochronology datasets in relation to tectonics can also provide important constraints on the growth of the fold-and-thrust belts (Wobus *et al.* 2003; Restrepo-Moreno *et al.* 2009; McQuarrie and Ehlers 2017). Combining thermochronology data with regional topographic profiles, river profiles and slope maps, and crustal-scale geological cross-sections, Jolivet *et al.* (2022) integrated tectonic, geomorphic and thermal pattern indicators to reveal three types of deformation modes including block uplift, distributed shortening and crustal buckling in the northern Tibetan plateau. In particular, distributed crustal shortening in the Qimen Tagh, northern Qaidam basin, and northern Qilian Shan was attributed to strike-slip faulting along the Altyn Tagh fault. On the other hand, the north–south-directed shortening in the Qilian Shan and southern Qaidam basin might be the result of crustal buckling. Vertical block uplift is responsible for the deformation in the Eastern Kunlun Shan. These modes of deformation can be compared with, and applied to, other fold-thrust belts globally.

The sedimentological records in basins associated with fold-and-thrust belts can be used to improve our understanding of the evolution of fold-and-thrust belt systems. Detrital geochronology has been widely used in tectonic, sedimentary, and basin analysis, as it is a powerful tool to characterize sediment source regions (Fedo *et al.* 2003; Gehrels 2014). However, uncertainties introduced by similar one-dimensional age spectra, numbers of the dated grains (e.g. zircon), and grain size of the zircons continue to hamper robust interpretation. To better compare the detrital geochronology datasets with similar age distributions, Saylor and Sundell (2021) developed new methods of sample intercomparison by incorporating a second variable data set (e.g. Hf isotopic data) and applying non-negative matrix factorization (NMF) to bivariate datasets. To verify this bivariate comparison approach, tens of published Neoproterozoic–Triassic samples from the western Laurentia were reanalysed. The results are consistent with our current understanding of the source-to-sink systems across different parts of the northern margin of Laurentia. Specifically, results show that the North American Transcontinental Arch was not a barrier to east–west sediment transport until the late Cambrian. The novel development and application of NMF to joint U–Pb–Hf datasets revealed a possible Permo-Triassic sediment source from northern South America following the assembly of Pangaea, which has implications for interpreting sediment provenance records in the Jurassic–Paleogene North American Cordillera retroarc foreland basin. This study reveals that NMF-based provenance analysis could be applied to foreland basin strata; this new method provides effective constraints on the sediment sources in transcontinental sediment transport systems. In addition, recognizing the sources and age distributions will provide a basic framework that can be used to more accurately interpret detrital analyses from Jurassic–Paleogene strata in western North America.

Different from the approaches mentioned above, flexural modelling can explore the balance between topographic loading and the distribution of the sediments in fold-and-thrust belts and associated foreland basins (Allen and Allen 2013; Cheng *et al.* 2019*a*; Wang *et al.* 2021). By using detrital zircon geochronology, palynology, magnetostratigraphy, ^{40}Ar/^{30}Ar dating on the Cenozoic strata in the Corque Syncline, Runyon *et al.* (2022) confirmed the deposition of the 7.4 km thick strata between 36.7 and 18.7 Ma. Moreover, using palaeoelevation estimates of the western Cordillera and Eastern Cordilleran as a guide, Runyon *et al.* (2022) revealed that the topographic load in both mountain belts is insufficient to account for the magnitude of subsidence based on the flexural modelling alone; this indicates that a subsidence mechanism beyond topographic flexure loading is responsible for the accumulated thickness. By integrating of the current understanding of deformation history, Runyon *et al.* (2022) proposed that subsidence was driven by a combination of flexure associated with surface loading and dynamic effects associated with flat-slab subduction since the Eocene–Oligocene.

Major phases of structural deformation may be recorded in the sedimentary records in the form of an unconformity due to uplift and erosion. Unconformities in the foreland basin are usually attributed to tectonic, climate, eustatic, and internally driven processes (Crampton and Allen 1995; DeCelles and Giles 1996). A better understanding of the mechanism for generating long-duration unconformities is essential to unravel the complex evolution of foreland basins and has important implications for the geodynamics of convergent plate boundaries. Horton (2022) introduced seven different mechanisms of unconformity development, including (1) shortening in the frontal thrust belt and proximal foreland; (2) uplift of intraforeland basement; (3) tectonic quiescence with regional isostatic rebound; (4) cessation of thrust loading and flexural subsidence during oblique convergence; (5) diminished accommodation or sediment supply due to changes in sea-level, climate, erosion or transport; (6) basin-wide uplift during flat-slab subduction; and (7) dynamic uplift associated with slab window formation, slab break-off, or elevated intraplate stress. These potential mechanisms are well-exemplified in the unconformities in the Andes and its retroarc foreland basin system. Based on high-resolution seismic profiles, Chen and He (2022) also explored the genesis of the growth unconformities in the Biertuokuoyi piggyback basin which is located in the hangingwall block of the Pamir Frontal Thrust in western China. By reconstructing the geometry and kinematics of structures beneath the basin, Chen and He (2022) suggested that the Biertuokuoyi piggyback basin and the Pamir Frontal Thrust are coupled. Pulsed thrusting of the Pamir Frontal Thrust is then interpreted based on six different growth uniformities in the basin. This work emphasizes the importance of using growth unconformities as a tool to document the evolution of the fold-and-thrust belts.

Finally, modern fold-thrust belts may develop in orogens that experience multiple phases of tectonic deformation. Some pre-existing structures, topographic relief, and other characteristics of orogenic belts will play an important role during the development of a fold-thrust belt (Darby and Ritts 2002; Zuza *et al.* 2018). Thus, a better knowledge of the growth history of orogenic belts is essential. The modern Qilian Shan is a fold-thrust belt that is developed on the Paleozoic accretionary orogenic belt of northern China. To provide a better constraint on the accretionary history of the Qilian Shan, Yan *et al.* (2021) focused on Ordovician strata in the northern Qilian Shan. Radiolarians and conodonts of the Floian-Dapingian age are observed in the cherts, indicating that early to middle Ordovician Ocean Plate Stratigraphy is part of a North Qilian Shan accretionary complex. The geochemical composition of 23 chert samples is similar to those of associated muddy siltstone, indicating near-trench sedimentation with minor terrestrial input. Integrated with published metamorphic ages in this region, this work proposes that the North Qilian Shan accretionary complex formed during the accretion process of ocean plate stratigraphic successions, driven by subduction of the Proto-Tethyan Ocean before early Paleozoic.

A collection of studies showed new methods and techniques to understand provenance in foreland basins, which will improve our understanding of the associated fold-and-thrust belt that drove basin formation through tectonic loading and syn-kinematic erosion.

However, several works in this collection also emphasized the complex nature of continental plate convergence, including variable types of strain partitioning between strike-slip and thrust faulting (Cheng *et al.* 2021) and differing modes of plate convergence including block uplift, distributed shortening and crustal buckling (Jolivet *et al.* 2022). These complexities will undoubtedly lead to different magnitudes and rates of exhumation, and thus differing patterns in crustal cooling tracked by low-temperature thermochronology. We suggest future studies explore the relationships between variable strain partitioning within the orogen and the associated response in range exhumation and basin sedimentation, with the ultimate goal of being able to interpret complex deformation kinematics from basin and thermochronology records. Further efforts are also needed for comparative studies of the fold-and-thrust belts around the world as different fold-and-thrust belts usually differ in distribution, geometry, and kinematics of structures. For instance, what can we learn from the different kinematic evolution of the fold-and-thrust belt in the northern Tibet, Himalayas, and the Andes regions? Comprehensive analyses of these differences enable us to provide crucial insights for recognizing the dominant factor that drives the growth of the fold-and-thrust belt, which contributes to a better understanding of the mechanism of fold-and-thrust in convergent settings in a broad view. As one of the most important structural units in the upper-crust, fold-and-thrust belts usually accumulate thick sedimentary rocks in the foreland basin (DeCelles 2011).

Given the tectonic deformation and basement exhumation in the mountain belts and the sedimentation in the foreland basin, fold-and-thrust belt systems are also the ideal place for research that explores interactions among climate, sedimentation, erosion, landscape evolution, and mountain building at regional or local scales (Dahlen and Suppe 1988; McQuarrie *et al.* 2008; Liu *et al.* 2020). Derived from the surrounding mountain belts or recycled sedimentary strata in the basin, these sediments in the foreland basin not only record the growth evolution of the fold-and-thrust belt but also can provide insights into palaeoclimate evolution. In particular, during extreme weather and climate events, such as the Paleocene–Eocene Thermal Maximum, the Eocene–Oligocene Transition, and Plio-Pleistocene Climate Transition, these sediments provide a window to explore regional palaeoclimate variations that respond to the global climate change. In summary, the improvement of our understanding of fold-and-thrust belt systems around the world not only helps better interpret geodynamic questions and understand past orogenic cycles but also promotes interdisciplinary research that lead to new insights and even more questions in a broader context.

Acknowledgements We thank Graham Shields, the Editor in Chief of the Journal of Geological Society, London, for providing this opportunity to gather this set of contributions. We are grateful to Bethan Littley and Patricia Pantoş for their editorial handling of this collection. We gratefully acknowledge all who contributed to the success of the AGU Fall Meeting session T21H: ‘Structure, sedimentation, and dynamics of fold-and-thrust belts and associated basins on Earth and other planets’ held in 2019, San Francisco. All the reviewers that evaluated the papers in this volume are highly appreciated.

Author contributions **FC**: conceptualization (lead), data curation (lead), funding acquisition (lead), investigation (lead), writing – original draft (lead), writing – review & editing (lead); **AVZ**: conceptualization (supporting), funding acquisition (supporting), validation (lead), writing – review & editing (lead); **YL**: conceptualization (supporting), investigation (supporting), resources (supporting), validation (supporting); **KS**: conceptualization (supporting), resources (supporting), validation (supporting), writing – review & editing (equal)

Funding We thank the support of the open grant from the Lhasa National Geophysical Observation and Research Station, Institute of Geology, China Earthquake Administration, Lhasa 850004, China (NORSLS20-01), and the open grant from the Yunnan Key Laboratory of Earth Science (ESS2021001) (awarded to FC). Support from the National Science Foundation (EARs 1914501, 1649254) is acknowledged by AVZ and KS.

Competing 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.

Data availability Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Scientific editing by Graham Shields

References

Allen, P.A. and Allen, J.R. 2013. *Basin Analysis: Principles And Application To Petroleum Play Assessment*. John Wiley & Sons.

Chapman, J.B. and DeCelles, P.G. 2015. Foreland basin stratigraphic control on thrust belt evolution. *Geology*, **43**, 579–582, https://doi.org/10.1130/g36597.1

Chapple, W.M. 1978. Mechanics of thin-skinned fold-and-thrust belts. *Geological Society of America Bulletin*, **89**, 1189–1198, https://doi.org/10.1130/0016-7606(1978)89<1189:MOTFB>2.0.CO;2

Chen, J. and He, D. 2022. Geometry, kinematics and mechanism of growth unconformities in the Biertuokuoyi piggy-back basin: implications for episodic growth of the Pamir frontal thrust. *Journal of the Geological Society, London*, **179**, jgs2021-100, https://doi.org/10.1144/jgs2021-100

Chen, H., Lin, X. *et al.* 2022. Two-phase intracontinental deformation mode in the context of India–Eurasia collision: insights from a structural analysis of the West Kunlun–Southern Junggar transect along the NW margin of the Tibetan Plateau. *Journal of the Geological Society, London*, **179**, jgs2021-029, https://doi.org/10.1144/jgs2021-029

Cheng, F., Garzione, C., Jolivet, M., Guo, Z., Zhang, D., Zhang, C. and Zhang, Q. 2019*a*. Initial deformation of the Northern Tibetan Plateau: insights from deposition of the Lulehe Formation in the Qaidam basin. *Tectonics*, **38**, 741–766, https://doi.org/10.1029/2018TC005214

Cheng, F., Garzione, C.N. *et al.* 2019*b*. The interplay between climate and tectonics during the upward and outward growth of the Qilian Shan Orogenic wedge, northern Tibetan Plateau. *Earth-Science Reviews*, **198**, 102945, https://doi.org/10.1016/j.earscirev.2019.102945

Cheng, F., Zuza, A.V. *et al.* 2021. Accommodation of India–Asia convergence via strike-slip faulting and block rotation in the Qilian Shan fold–thrust belt, northern margin of the Tibetan Plateau. *Journal of the Geological Society, London*, **178**, jgs2020-207, https://doi.org/10.1144/jgs2020-207

Crampton, S.L. and Allen, P.A. 1995. Recognition of Forebulge Unconformities Associated with Early Stage Foreland Basin development: example from the North Alpine Foreland Basin1. *AAPG Bulletin*, **79**, 1495–1514, https://doi.org/10.1306/7834DA1C-1721-11D7-8645000102C1865D

Dahlen, F. 1990. Critical taper model of fold-and-thrust belts and accretionary wedges. *Annual Review of Earth and Planetary Sciences*, **18**, 55–99, https://doi.org/10.1146/annurev.ea.18.050190.000415

Dahlen, F. and Suppe, J. 1988. Mechanics, growth, and erosion of mountain belts. *Processes in Continental Lithospheric Deformation: Geological Society of America Special Paper*, **218**, 161–178, https://doi.org/10.1130/SPE218-p161

Darby, B.J. and Ritts, B.D. 2002. Mesozoic contractional deformation in the middle of the Asian tectonic collage: the intraplate Western Ordos fold–thrust belt, China. *Earth and Planetary Science Letters*, **205**, 13–24, https://doi.org/10.1016/S0012-821X(02)01026-9

Davis, D., Suppe, J. and Dahlen, F. 1983. Mechanics of fold-and-thrust belts and accretionary wedges. *Journal of Geophysical Research: Solid Earth*, **88**, 1153–1172, https://doi.org/10.1029/JB088iB02p01153

DeCelles, P.G. 2011. Foreland basin systems revisited: variations in response to tectonic settings. *In*: Busby, C. and Azor, A. (eds) *Tectonics of Sedimentary Basins. Recent Advances*. Wiley–Blackwell, Oxford, 405–426, https://onlinelibrary.wiley.com/doi/10.1002/9781444347166.ch20

DeCelles, P.G. and Giles, K. 1996. Foreland basin systems. *Basin Research*, **8**, 105–123, https://doi.org/10.1046/j.1365-2117.1996.01491.x

Fedo, C.M., Sircombe, K.N. and Rainbird, R.H. 2003. Detrital zircon analysis of the sedimentary record. *Reviews in Mineralogy and Geochemistry*, **53**, 277–303, https://doi.org/10.2113/0530277

Gabrielsen, R.H., Roberts, D., Gjelsvik, T., Sygnabere, T.O., Hassaan, M. and Faleide, J.I. 2022. Double-folding and thrust-front geometries associated with the Timanian and Caledonian orogenies in the Varanger Peninsula, Finnmark, North Norway. *Journal of the Geological Society, London*, **179**, jgs2021-153, https://doi.org/10.1144/jgs2021-153

Gehrels, G. 2014. Detrital zircon U-Pb geochronology applied to tectonics. *Annual Review of Earth and Planetary Sciences*, **42**, 127–149, https://doi.org/10.1146/annurev-earth-050212-124012

Horton, B.K. 2022. Unconformity development in retroarc foreland basins: implications for the geodynamics of Andean-type margins. *Journal of the Geological Society, London*, **179**, jgs2020-263, https://doi.org/10.1144/jgs2020-263

Horton, B.K. and DeCelles, P.G. 2001. Modern and ancient fluvial megafans in the foreland basin system of the central Andes, southern Bolivia: implications for drainage network evolution in fold-thrust belts. *Basin Research*, **13**, 43–63, https://doi.org/10.1046/j.1365-2117.2001.00137.x

Jia, C., Li, B., Lei, Y. and Chen, Z. 2013. The structure of circum-tibetan plateau basin-range system and the large gas provinces. *Science China Earth Sciences*, **56**, 1853–1863, https://doi.org/10.1007/s11430-013-4649-7

Jolivet, M., Cheng, F., Zuza, A.V., Guo, Z. and Dauteuil, O. 2022. Large-scale topography of the north Tibetan ranges as a proxy for contrasted crustal-scale deformation modes. *Journal of the Geological Society, London*, **179**, jgs2021-085, https://doi.org/10.1144/jgs2021-085

Liu, Y., Tan, X. *et al.* 2020. Role of erosion in creating thrust recesses in a critical-taper wedge: an example from Eastern Tibet. *Earth and Planetary Science Letters*, **540**, 116270, https://doi.org/10.1016/j.epsl.2020.116270

McQuarrie, N. and Ehlers, T.A. 2017. Techniques for understanding fold-and-thrust belt kinematics and thermal evolution. *In*: Law, R.D., Thigpen, J.R., Merschat, A.J. and Stowell, H.H. *Linkages and Feedbacks in Orogenic Systems*. Geological Society of America, 25–54.

McQuarrie, N., Ehlers, T.A., Barnes, J.B. and Meade, B. 2008. Temporal variation in climate and tectonic coupling in the central Andes. *Geology*, **36**, 999–1002, https://doi.org/10.1130/G25124A.1

Namson, J.S. and Davis, T.L. 1988. Seismically active fold and thrust belt in the San Joaquin Valley, central California. *Geological Society of America Bulletin*, **100**, 257–273, https://doi.org/10.1130/0016-7606(1988)100<0257:SAFATB>2.3.CO;2

Restrepo-Moreno, S.A., Foster, D.A., Stockli, D.F. and Parra-Sánchez, L.N. 2009. Long-term erosion and exhumation of the 'Altiplano Antioqueño', Northern Andes (Colombia) from apatite (U–Th)/He thermochronology. *Earth and Planetary Science Letters*, **278**, 1–12, https://doi.org/10.1016/j.epsl.2008.09.037

Roure, F., Choukroune, P. *et al.* 1989. Ecors deep seismic data and balanced cross sections: geometric constraints on the evolution of the Pyrenees. *Tectonics*, **8**, 41–50, https://doi.org/10.1029/TC008i001p00041

Runyon, B., Saylor, J.E., Horton, B.K., Reynolds, J.H. and Hampton, B. 2022. Basin evolution in response to flat-slab subduction in the Altiplano. *Journal of the Geological Society, London*, **179**, jgs2021-003, https://doi.org/10.1144/jgs2021-003

Saylor, J.E. and Sundell, K.E. 2021. Tracking Proterozoic–Triassic sediment routing to western Laurentia via bivariate non-negative matrix factorization of detrital provenance data. *Journal of the Geological Society, London*, **178**, jgs2020-215, https://doi.org/10.1144/jgs2020-215

Suppe, J. and Medwedeff, D.A. 1990. Geometry and kinematics of fault-propagation folding. *Eclogae Geologicae Helvetiae*, **83**, 409–454.

Tavani, S., Storti, F., Lacombe, O., Corradetti, A., Muñoz, J.A. and Mazzoli, S. 2015. A review of deformation pattern templates in foreland basin systems and fold-and-thrust belts: Implications for the state of stress in the frontal regions of thrust wedges. *Earth-Science Reviews*, **141**, 82–104, https://doi.org/10.1016/j.earscirev.2014.11.013

Tucker, G.E. and Slingerland, R. 1996. Predicting sediment flux from fold and thrust belts. *Basin Research*, **8**, 329–349, https://doi.org/10.1046/j.1365-2117.1996.00238.x

Wang, L., Cheng, F. *et al.* 2021. Diachronous growth of the Northern Tibetan plateau derived from flexural modeling. *Geophysical Research Letters*, **48**, e2020GL092346, https://doi.org/10.1029/2020GL092346

Wobus, C.W., Hodges, K.V. and Whipple, K.X. 2003. Has focused denudation sustained active thrusting at the Himalayan topographic front? *Geology*, **31**, 861–864, https://doi.org/10.1130/G19730.1

Woodward, N.B., Boyer, S.E. and Suppe, J. 1989. *Balanced Geological Cross-Sections: An Essential Technique in Geological Research and Exploration*, 1–126, https://doi.org/10.1002/9781118667354.ch1

Yan, Z., Xiao, W., Aitchison, J.C., Yuan, C., Liu, C. and Fu, C. 2021. Age and origin of accreted ocean plate stratigraphy in the North Qilian belt, NE Tibet Plateau: evidence from microfossils and geochemistry of cherts and siltstones. *Journal of the Geological Society, London*, **178**, jgs2020-231, https://doi.org/10.1144/jgs2020-231

Zuza, A., Wu, C. *et al.* 2018. Tectonic evolution of the Qilian Shan: an early Paleozoic orogen reactivated in the Cenozoic. *Geological Society of America Bulletin*, **130**, 881–925, https://doi.org/10.1130/B31721.1