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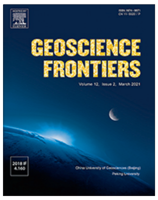

Editorial

# Metamorphism at convergent plate margins: Preface

## 1. Foreword

The year 2020 will long be recognised as a period of sadness and frustration for academics worldwide, given the catastrophic impact that the spread of novel coronavirus "2019-nCoV" – or COVID-19 – has had on research and teaching activities, as well as in their personal lives. This Special Issue was designed to represent an avenue for dissemination of many studies presented at the September 2019 Geological Society of America session T23, 'Metamorphism and Orogenesis at Convergent Plate Margins', convened by Richard Palin and Kyle Ashley. Many geologists at all career stages attended this session and presented work that was in different stages of completion; however, just a few months later, the rapid spread of COVID-19 around the globe applied sudden brakes to many of these partially completed projects. Several researchers who expressed interest in contributing to this Special Issue were forced to withdraw, either due to new responsibilities at home, laboratory closures at their places of work, or restrictions halting domestic or international travel. We appreciate that these changes in circumstance have resulted in fewer than expected contributions to this Special Issue, and warmly thank the authors who did manage to overcome these hurdles and produce an excellent set of papers. We hope that the academic world will be able to recover from the impact of COVID-19 so that we can – as a community – move forward once again to break new ground in our understanding of this dynamic and highly unpredictable natural world.

## 2. Introduction

Convergent plate margins are sites of intense deformation, metamorphism, and magmatism, where significant heat, fluid, and mass transfer may take place. Quantifying the fluxes and drivers of orogenic processes in these regions is critical to understanding the geodynamical evolution of the lithosphere, the rates and mechanisms of metamorphism at elevated pressure and temperature conditions, and for constraining the nature of mountain building and continental growth through geological time. Investigating the drivers and petrological/tectonic implications of regional or contact metamorphism at convergent plate margins, whether in the subducting slab or overlying arc, can be achieved via many techniques, such as field mapping, petrological phase equilibrium modelling, petrochronology, geochemistry, and geodynamic and/or geophysical modelling, and which can be performed a wide range of spatial and/or temporal scales (e.g. Hossack, 1979; Bell and Johnson 1989; Li and Bebout, 2005; Roberts, 2012; St-Onge et al., 2013; Palin and White, 2016; Palin et al., 2020). The contributions to this Special Issue exemplify innovative uses of combinations of these techniques, and address important questions related both to local geology and broader-scale geodynamic processes.

## 3. Contributions in this Special Issue

This Special Issue of Geoscience Frontiers assembles seven papers authored by a geographically diverse set of scientists at various career stages. Together, these studies focus on deformational, magmatic and metamorphic processes that occur in several continental arcs and collision zones worldwide, and spanning the Mesoproterozoic to recent.

The first study, by Avellaneda-Jiménez et al. (2022), presents new field observations, petrological data, and results of thermobarometry from Early Cretaceous, metamorphic rocks in the Central Cordillera of the Colombian Andes. These outcrops preserve metabasites that experienced cold and steep subduction to eclogite-facies conditions, followed by thermal overprinting to amphibolite-facies conditions during buoyancy-driven exhumation. High-resolution constraints on the pressure and temperature evolution indicate a secular evolution in the thermal structure of the subduction channel, which the authors interpret as evidence for asthenospheric mantle inflow during steepening of the angle of subduction of the oceanic lithosphere through time. Such processes are hypothesized to have occurred throughout Earth history (Smith et al., 2014; Wang et al., 2019; Parsons et al., 2020), with this contribution marking the first report of Phanerozoic slab roll-back-related metamorphism in the Caribbean.

Next, Larson et al. (2022) present new petrological analyses, results of thermobarometry, and garnet Lu–Hf age data from a sample of metapelitic schist from the Nepalese Himalaya, which reveal that the basal décollement oscillated "in and out of sequence" through time as the orogenic hinterland evolved during the Miocene. Such data may contribute to new kinematic models describing how continent–continent collisional orogenesis evolves through time. These data from east–central Nepal are correlated by the authors with similar examples in west Nepal (Soucy La Roche et al., 2018), Bhutan (Grujic et al., 2011), and northeast India (Warren et al., 2014), showing that this is likely a broad-scale feature of the Himalaya, and not a localized phenomenon.

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The third study, by Searle and Lamont (2022), reviews the geological evolution of the Cyclades, and in particular, a recently proposed and highly provocative hypothesis that the entire tectonothermal history of the Cycladic islands – including Naxos, Tinos and Syros – can be explained by continent–continent collision (e.g. Lamont et al., 2020a; Lamont et al., 2020b; Searle and Lamont, 2020) instead of representing metamorphism in an extending back-arc region (e.g. Lister et al., 1984; Jolivet and Brun, 2010; Menant et al., 2016). The authors outline a detailed geodynamic model relating all known stages of the Wilson Cycle to various localities throughout the region, which developed over a 70-Myr period. The suggestion that the Cyclades may have formed in this way will no doubt beg the question of whether other apparently 'well understood' examples of actively extending continental lithosphere associated with orogenic collapse of previously thickened crust may instead have formed in a similar fashion.

The following study, by Sequeira et al. (2022), presents metamorphic conditions, geochronology and magmatic geochemistry from the Chottanagpur Gneiss Complex (CGC) of Eastern India. The CGC represents an accretionary zone where crustal blocks of northern and southern India collided in the early Neoproterozoic. This study documents a ca. 1.5–1.4 Ga suite of A-type granitoids, which are interpreted as a widespread phase of magmatism involving extension and asthenospheric upwelling, and correlate with A-type magmatism elsewhere in the Columbia supercontinent. This magmatism postdates early metamorphism and deformation at >1.5 Ga in the CGC, and pre-dates 1.0–0.9 Ga metamorphism and deformation associated with amalgamation of crustal blocks along this fold belt. The origin and amalgamation of crustal blocks of Greater India during the Columbia to Rodinia supercontinent transition is highly debated, with this study presenting crucial new evidence for this puzzle.

The fifth study, by Shakerardakani et al. (2022), presents geochronology and metamorphic petrology from the Sanandaj-Sirjan Zone of the Zagros mountains in Iran. Two different units are interrogated, and both provide evidence of Variscan-aged (late Carboniferous) high temperature/low pressure metamorphism and rift-related bimodal magmatism. The next metamorphic event is not well constrained, but evidence is presented for an Early Jurassic high pressure/low temperature event, with potentially related contact metamorphism. The late Cretaceous to early Paleogene collision of Neotethys is recorded as M3 metamorphism in the studied units. A final metamorphic stage (M4) is observed, with timing constrained to ca. 28 Ma to 25 Ma, but the origin of which remains elusive. This study demonstrates the polymetamorphic nature of the Zagros mountains, and provides areas of interest for further detailed invesitigation with constrained P-T-t paths. The younger metamorphic stages will potentially inform about the overall evolution of the Neotethys collisional belt.

Next, Walczak et al. (2022) present new geochronological data for felsic orthogneiss from the Seve Nappe Complex, Scandinavian Caledonides, using a zircon age depth-profiling method. The careful analysis of thin zircon rims and overgrowths is shown by the authors to document two discrete subduction and (partial) exhumation events separated by ca. 20 Myr; affectionately referred to as double-dunking! Such yo-yo tectonics at convergent margins have been reported in rocks from Turkey (Umhoefer et al., 2007) and the Italian Alps (Rubatto et al., 2011), and require high-spatial resolution geochronology to identify; thus, they may be a common feature of metamorphism at convergent margins, but have been formerly missed in studies that have not had access to these newly developed analytical techniques.

The final study by Zuza et al. (2022) documents critical field observations and petrological data supporting a highly contentious theory that has arisen in recent years – that tectonic pressure within deforming continental crust can significantly exceed that expected solely induced by the volume of overburden (Petrini and Podladchikov, 2000; Moulas et al., 2013; Gerya, 2015). This contentious phenomenon is termed 'overpressure' and has been proposed based on the results of crustal-scale numerical modelling and first-principles calculations of mechanical/elastic interactions between different minerals at the grain scale (Schmalholz and Podladchikov, 2013; Wheeler, 2014; Tajčmanová et al., 2015); however, evidence of overpressure in the natural world has been difficult to discover. Recent workers have reported such occurrences in the Alps (Luisier et al., 2019) and potentially also the Himalaya (Marques et al., 2018). The authors provide a valuable addition to this list with evidence from the North American Cordillera.

We thank all the contributors to this Special Issue and the referees who spared their valuable time to provide insightful and helpful comments. Dr. L. Wang, Editorial Assistant at Geoscience Frontiers, and Prof. Santosh, Editorial Advisor, are also thanked for their support throughout the production process. We hope that the papers assembled herein will be of interest to many researchers worldwide for many years to come.

## Declaration of Competing Interest

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.

## References

Avellaneda-Jiménez, D.S., Cardona, A., Valencia, V., León, S., Blanco-Quintero, I.F., 2022. Metamorphic gradient modification in the Early Cretaceous Northern Andes subduction zone: A record from thermally overprinted high-pressure rocks. Geosci. Front. 13 (2), 1090. doi:10.1016/j.gsf.2020.09.019.

Bell, T.H., Johnson, S.E., 1989. Porphyroblast inclusion trails: the key to orogenesis. J. Metamorph. Geol. 7 (3), 279–310.

Gerya, T., 2015. Tectonic overpressure and underpressure in lithospheric tectonics and metamorphism. J. Metamorph. Geol. 33 (8), 785–800.

Grujic, D., Warren, C.J., Wooden, J.L., 2011. Rapid synconvergent exhumation of Miocene-aged lower orogenic crust in the eastern Himalaya. Lithosphere 3 (5), 346–366.

Hossack, J.R., 1979. The use of balanced cross-sections in the calculation of orogenic contraction: A review. J. Geol. Soc. 136 (6), 705–711.

Jolivet, L., Brun, J.-P., 2010. Cenozoic geodynamic evolution of the Aegean. Int. J. Earth Sci. 99 (1), 109–138.

Lamont, T.N., Roberts, N.M.W., Searle, M.P., Gopon, P., Waters, D.J., Millar, I., 2020a. The age, origin, and emplacement of the Tsiknias Ophiolite, Tinos, Greece. Tectonics 39, e2019TC005677.

Lamont, T.N., Searle, M.P., Waters, D.J., Roberts, N.M.W., Palin, R.M., Smye, A., Dyck, B., Gopon, P., Weller, O.M., St-Onge, M.R., 2020b. Compressional origin of the Naxos metamorphic core complex, Greece: Structure, petrography, and thermobarometry. Geol. Soc. Am. Bull. 132, 149–197.

Larson, K.P., Shrestha, S., Soret, M., Smit, M., 2022. The P–T–t–D evolution the Mahabharat, east-central Nepal: The out-of-sequence development of the Himalaya. Geosci. Front. 13 (2), 1057. doi: 10.1016/j.gsf.2020.08.001.

Li, L., Bebout, G.E., 2005. Carbon and nitrogen geochemistry of sediments in the Central American convergent margin: Insights regarding subduction input fluxes, diagenesis, and paleoproductivity. J. Geophys. Res. Solid Earth 110 (B11). https://doi.org/10.1029/2004JB003276.

Lister, G.S., Banga, G., Feenstra, A., 1984. Metamorphic core complexes of Cordilleran type in the Cyclades, Aegean Sea, Greece. Geology 12, 221–225.

Luisier, C., Baumgartner, L., Schmalholz, S.M., Siron, G., Vennemann, T., 2019. Metamorphic pressure variation in a coherent Alpine nappe challenges lithostatic pressure paradigm. Nat. Commun. 10, 1–11.

Marques, F.O., Mandal, N., Ghosh, S., Ranalli, G., Bose, S., 2018. Channel flow, tectonic overpressure, and exhumation of high-pressure rocks in the Greater Himalayas. Solid Earth 9 (5), 1061–1078.

Menant, A., Jolivet, L., Vrielynck, B., 2016. Kinematic reconstructions and magmatic evolution illuminating crustal and mantle dynamics of the eastern Mediterranean region since the late Cretaceous. Tectonophysics 675, 103–140.

Moulas, E., Podladchikov, Y.Y., Aranovich, L.Y., Kostopoulos, D., 2013. The problem of depth in geology: When pressure does not translate into depth. Petrology 21 (6), 527–538.

Palin, R.M., Santosh, M., Cao, W., Li, S.-S., Hernández-Uribe, D., Parsons, A., 2020. Secular change and the onset of plate tectonics on Earth. Earth-Sci. Rev. 207, 103172. https://doi.org/10.1016/j.earscirev.2020.103172.

Palin, R.M., White, R.W., 2016. Emergence of blueschists on Earth linked to secular changes in oceanic crust composition. Nat. Geosci. 9 (1), 60–64.

Parsons, A.J., Hosseini, K., Palin, R.M., Sigloch, K., 2020. Geological, geophysical and plate kinematic constraints for models of the India-Asia collision and the post-Triassic central Tethys oceans. Earth-Sci. Rev. 208, 103084.

Petrini, K., Podladchikov, Y., 2000. Lithospheric pressure–depth relationship in compressive regions of thickened crust. J. Metamorph. Geol. 18, 67–77.

Roberts, N.M.W., 2012. Increased loss of continental crust during supercontinent amalgamation. Gondwana Res. 21 (4), 994–1000.

Rubatto, D., Regis, D., Hermann, J., Boston, K., Engi, M., Beltrando, M., McAlpine, S.R.B., 2011. Yo-yo subduction recorded by accessory minerals in the Italian Western Alps. Nat. Geosci. 4 (5), 338–342.

Schmalholz, S.M., Podladchikov, Y.Y., 2013. Tectonic overpressure in weak crustal-scale shear zones and implications for the exhumation of high-pressure rocks. Geophys. Res. Lett. 40 (10), 1984–1988.

Searle, M.P., Lamont, T.N., 2020. Compressional metamorphic core complexes, low-angle normal faults and extensional fabrics in compressional tectonic settings. Geol. Mag. 157, 101–118.

Searle, M.P., Lamont, T.N., 2022. Compressional origin of the Aegean Orogeny, Greece. Geosci. Front. 13 (2), 1049. doi: 10.1016/j.gsf.2020.07.008

Sequeira, N., Bhattacharya, A., Bell, E., 2022. The ~ 1.4 Ga A-type granitoids in the “Chottanagpur crustal block” (India), and its relocation from Columbia to Rodinia? Geosci. Front. 13 (2), 101138. https://doi.org/10.1016/j.gsf.2020.12.017.

Shakerardakani, F., Neubauer, F., Bernroider, M., Finger, F., Hauzenberger, C., Genser, J., Waitzinger, M., Monfaredi, B., 2022. Metamorphic stages in mountain belts during a Wilson cycle: A case study in the central Sanandaj-Sirjan zone (Zagros Mountains, Iran). Geosci. Front. 13 (2), 101272.

Smith, M.E., Carroll, A.R., Jicha, B.R., Cassel, E.J., Scott, J.J., 2014. Paleogeographic record of Eocene Farallon slab rollback beneath western North America. Geology 42, 1039–1042.

Soucy La Roche, R., Godin, L., Cottle, J.M., Kellett, D.A., 2018. Preservation of the early evolution of the Himalayan middle crust in foreland klippen: insights from the Karnali klippe, west Nepal. Tectonics 37 (5), 1161–1193.

St-Onge, M.R., Rayner, N., Palin, R.M., Searle, M.P., Waters, D.J., 2013. Integrated pressure–temperature–time constraints for the Tso Morari dome (Northwest India): implications for the burial and exhumation path of UHP units in the western H imalaya. J. Metamorph. Geol. 31 (5), 469–504.

Tajčmanová, L., Vrijmoed, J., Moulas, E., 2015. Grain-scale pressure variations in metamorphic rocks: implications for the interpretation of petrographic observations. Lithos 216-217, 338–351.

Umhoefer, P.J., Whitney, D.L., Teyssier, C., Fayon, A.K., Casale, G., Heizler, M.T., 2007. Yo-yo tectonics in a wrench zone, Central Anatolian fault zone, Turkey. In: Till, A.B., Roeske, S.M., Sample, J.C., and Foster, D.A. (Eds.), Exhumation Associated with Continental Strike-Slip Fault Systems. Geological Society of America Special Paper 434, 35–57.

Walczak, K., Majka, J., Gee, D.G., Klonowska, I., 2022. Zircon age depth-profiling sheds light on the early Caledonian evolution of Seve Nappe Complex in west-central Jämtland. Geosci. Front. 13 (2), 101112. https://doi.org/10.1016/j.gsf.2020.11.009.

Wang, R., Xu, Z., Santosh, M., 2019. Neoproterozoic magmatism in the northern margin of the Yangtze Block, China: Implications for slab rollback in a subduction-related setting. Precambrian Res. 327, 176–195.

Warren, C.J., Singh, A.K., Roberts, N.M.W., Regis, D., Halton, A.M., Singh, R.B., 2014. Timing and conditions of peak metamorphism and cooling across the Zimithang Thrust, Arunachal Pradesh, India. Lithos 200-201, 94–110.

Wheeler, J., 2014. Dramatic effects of stress on metamorphic reactions. Geology 42, 647–650.

Zuza, A.V., Levy, D.A., Mulligan, S., 2022. Geologic field evidence for non-lithostatic overpressure recorded in the North American Cordillera hinterland, northeast Nevada. Geosci. Front. 13 (2), 101099. https://doi.org/10.1016/j.gsf.2020.10.006.

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