Lithospheric warping underlies the formation of back-arc basins

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Lithospheric warping underlies the formation of back-arc basins

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Back-arc basins represent intriguing phenomenon of the lithospheric evolution. They are the places of potential subduction initiation, what makes them highly important features within the theory of plate tectonics. The circumstances of their origin and life cycle are not well understood and whether the retreat of subduction is a cause or consequence of back-arc basin development remains an open issue. In the presented work, the new approach has been used, based on the model of thin shell warping. Within this concept, the plate warps due to proximity of translational boundary when its forward movement is constrained. During the process, the lithospheric slab can steepen and sink to the 660 km transition layer, reaching an amphitheatre-like geometry. The specific shape of deformation resembles the topology of several reference basins from the Western Pacific region. Results show that subduction retreat, back-arc extension and arcuate geometry may represent only different demonstrations of one underlying physical mechanism. Modelling suggests that the movement of plates and their interactions, together with the curvature of the Earth's surface, could be responsible for the formation of back-arc basins.

The volcanic island arcs, with trenches in front and the basins at their rear, are still puzzling features despite an enormous amount of new data, observations and computer modelling. The question of why they are of arcuate shape has remained largely unresolved. These structures are inherently linked to the subduction of oceanic lithosphere and thus their geometry has been interpreted as its product. It comes from the trivial assumption that sinking slab should adjust to the spherical surface[1]. This concept has been disproved at several points [2,3,4], but there are still attempts at revival of such "ping-pong ball" model[5]. The main problem of this hypothesis is that a lot of of these zones are retreating and changing their curvature. This would inevitably lead to the slab tearing into pieces. Despite the indications that Earth's curvature could be nevertheless the cause of arcuate shapes, no new proposal of such a connection has been given.

Following the observations of Karig[6], occurrence of extension within these regions was explained by motion of the overriding plate away from the subduction front[7,8]. On the other side Molnar and Atwater[9] proposed the hinge retreat as a consequence of the lithosphere sinking under its own weight. A compromise between the two cases was the combination of slab hinge migration (or roll-back) with the overriding plate motion[10]. The subduction roll-back became popular due to extensive capabilities of analogous and numerical modelling. If not for two exceptions, the concept of roll-back with hinge retreat would apply to all arc-back-arc systems. But formation of back-arc basins in front of advancing hinges at Izu-Bonin[11] and Mariana[12] subductions raises concerns about universality of such a mechanism. Furthermore, the fact that in some cases (Japan Sea basin, South Fiji Sea basin) back arc extension came to an end while subduction continued, indicates that subduction is not a sufficient condition for back-arc opening.

Another question is what the slab steepening might mean for the back-arc evolution[4]. Analogue experiments clearly showed that subduction can result in a slab simply falling to the mantle, instead of trench retreat and roll-back[13]. It is also not clear whether we have enough evidence that trenches migrate at the same speed as volcanic arcs. Therefore, because slab roll-back alone cannot explain either the back-arc basins formation or arc curvature, other processes must be involved. Back-arc systems generally evolve in convergent settings, where shortening occurs along the convex forearc segment and extension at the rear, concave side. Consistent tectonic models should therefore take this under the consideration. The concept with such presumption has become extrusion due to the collision, stressed by several authors [14,15,16]. But again, extension in the back-arc cannot be solely explained by extrusion[2] and mantle upwelling processes must be engaged [17,18]. Subduction retreat to arcuate shape in these models is as well rather consequence than the cause of back-arc basin formation.

On this account, young subduction zones connected to marginal basins should be important places to observe these processes. Such examples are Philippines and North Sulawesi areas, where there is an evident extension behind subducting lithosphere without volcanic arc presence. It has been proposed by Hall, 2019[19] that these are actually new-born subduction zones, originated by thrusting of the marginal lithosphere onto the oceanic one. Young back-arc basins have been also chosen as examples to this conceptual study. Due to their pronounced arcuate shape, slab geometry and position, Banda Sea, Bismarck Sea and Andaman Sea basins (Fig.1) serve as a reference for comparison with modelling results.

As demonstrated, there is no general consensus on these issues. Many models assign the decisive role in the origin of back-arc basins to the subduction, while some combine it with extrusion or others view subduction only as a moving boundary. It is then important to ask what is the connection between the two phenomena and if subduction is not only the by-product of the back-arc basins origin.

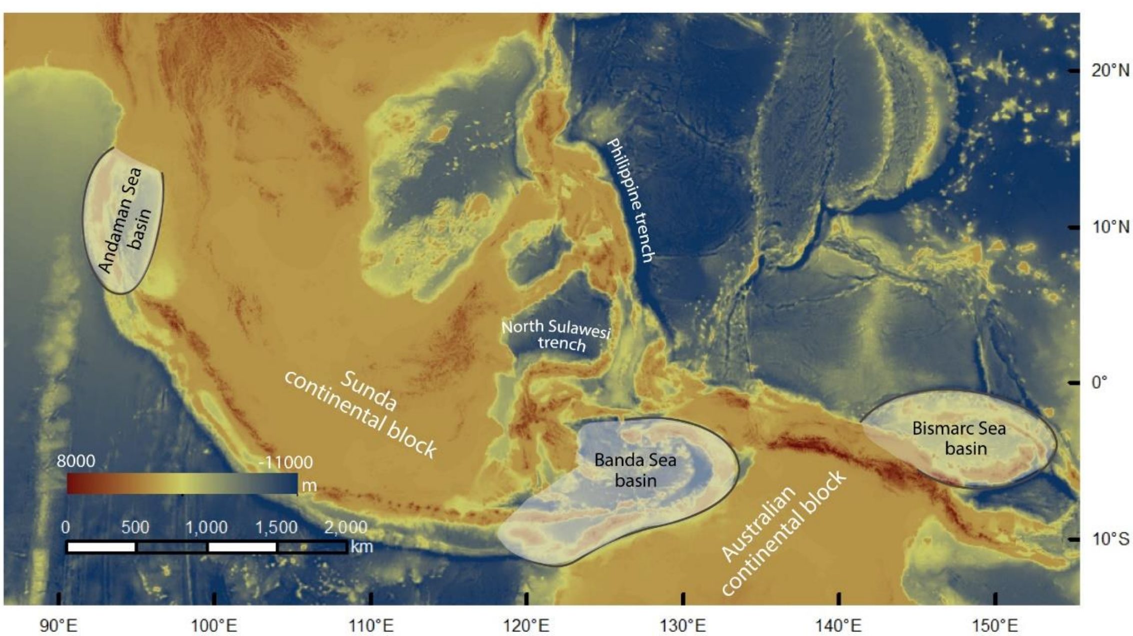

Fig. 1. Location map of the reference back-arc basins. Shaded areas show extent and shape of the structures, labelled trenches are considered to be young or incipient.

Modelling of the shell-related lithospheric deformations

To investigate the significance of convergence-related processes for back-arc evolution, attention has been focused on the thin shell deformation. Model configuration should represent lithospheric plate, approximated by viscoelastic layer of cylindrical shape, variously constrained at the sides. The material of the shell is given properties, commonly utilised for flexure modelling of viscoelastic plates (ref. [20]). All these properties can be adjusted. Movement of the plate is simulated by axial load applied on one edge of the shell, which is an approach used in the analogue models. The dimensions of the plate are 1000x1000 km (1000x1000 mm respectively), two values of thickness have been chosen, 10 and 20 km (10 mm and 20 mm respectively). Thickness of the shell fundamentally influences modelling and it is the most important parameter. With the exception of the central support at the frontal edge, which is stationary, all other parts can move during deformation. Side edges must be constrained against translations diverging from the direction of load. After meshing the model, basic static analysis is run in a solver module. Resulting deformed shell can be further scaled and covered with various contour types. Results are available either as a simple mesh or a coloured contours of the membrane force on the surface (Fig. 2). Progress of warping is captured step by step and presented as an animation.

During the simulation, unusually complex downwarp develops and deepens quickly, folding the shell in a specific manner (Supplementary Video 1). This is because curved layers have a unique capability to transform loads into membrane deformations instead of bending as with flat plates. Therefore the Earth's surface curvature could principally influence the behaviour of deforming lithospheric plate. It is of note that such pronounced vertical deformation develops from a pure horizontal force application and without other initial conditions added.

As a consequence of loading, the shell contracts in length and the wave movement of lateral surfaces folds them down significantly. The structure is forming into an arcuate appearance and even though deformation progresses quickly (Supplementary Video 1), its overall topology and horizontal extent changes little. Such stationary character brings potential for downside movements of large magnitude with only a little amount of convergence. The resulting deformation keeps its oval or candle-flame topology visible throughout duration of the whole process (Fig. 2a, b, c, d). Transformed to lithospheric conditions, deformation would be situated in the middle part of the lithosphere (oceanic or transient marginal), where properties of the material are suitable to maintain a viscoelastic response. Deformations of shells with about 10 km thickness are the most appropriate to show the nature of described process. One another analyse (20 km thickness) has been ran for evaluating the results of thickness changes on the shell deformation (Supplementary Video 2).

In order to better visualize arcuate shape of evolving deformation, cross-section has been constructed by the horizontal plane. Its position has been chosen at 100 km isohypse, depth of the magma production at subduction zones. Spreading of this oval-shaped structure should represent the back-arc outer propagation (Supplementary Video 3). Projection of such a cut to the surface level should approximate volcanic arc position (Fig. 2a, b, c). One vertical cross-section visualizes final slab position with amphitheatre-like geometry and serves as background for model based reconstruction of reference back-arc basin (Fig.3).

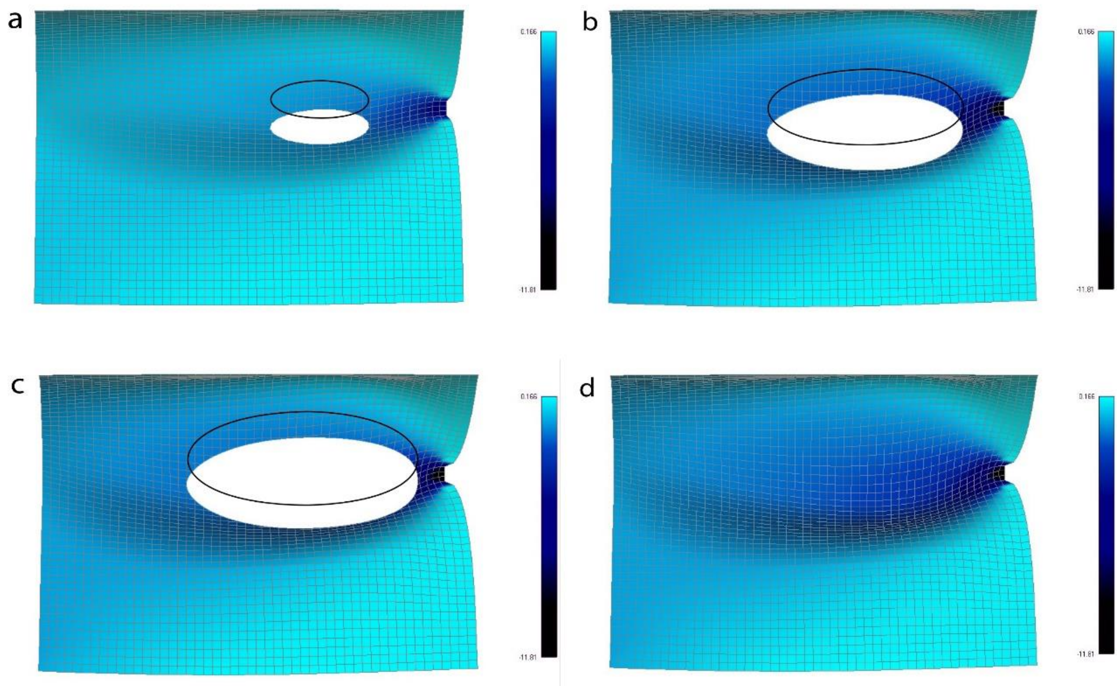

Fig. 2. Model of deformation development and arc propagation. Figures 2a and 2b show snapshots from model animation in times appr. one third and one half of the whole process duration, Figures 2c and 2d are the final state (with the cut and without it, respectively). Horizontal clipping planes are situated at the level of appr.100 km from the original surface, where melting of the slab causes magma ascent and volcanic arc origin. Its projection upward is visualised by the black ring. Colouring of the model represents continuous contours of membrane force in Nm^{-1}.

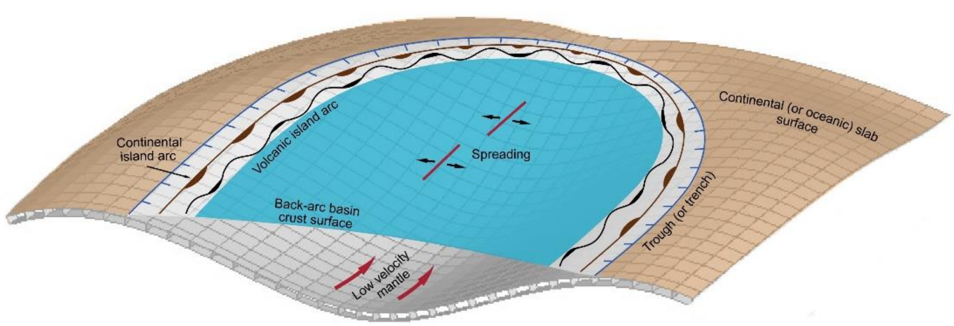

Fig. 3. Schematic cartoon showing the model based back-arc basin structure. It is drawn onto the vertical cross section of the model stage, shown in Figure 2d. Arcuate features are situated along the rim, whereas linear create centre of the basin (blue shading). Mantle ascent into the extending space and pressure release cause melting under the spreading ridges. The lithosphere surrounding back-arc (brown shading) is usually continental from one side and oceanic from the other (but can be also oceanic on both sides).

Predictions of the model and its connection to subduction dynamics

Extended crust at the continent margins or crustal remnants in the oceans have a transitional character and mechanical properties with effective elastic thickness usually between 10 and 20 km[21]. Considering the model is solely geometrical (intended to observe changing topology of the back-arc in 3D), reduction of the lithospheric structure into one viscoelastic layer can be feasible approximation of the physical reality[22]. Such approximations are largely used in studies of the subducting slabs geometries. Another assumption is that central constraint (support) is stationary in the model. In reality, the boundaries move, but because deformation appearance is little dependent on the load magnitude (it only approximates the plate motion), the boundary movement does not influence the results to a great extent. It is important to realise, that plate motion is only constrained, not restricted. Therefore deformation, as its part, also moves with plate.

Since the yielding of this lithospheric layer is a long-term process, it cannot be suddenly accelerated by an increase in the convergence rate. Changes likely happen on the geological time scale hundreds of thousands of years. This is also the limitation of the model, which provides only relative timing. Warping deformations induce flow in the surrounding mantle they are submerged (Fig.3) what also consumes energy and influences reaction times[22]. Due to this tendency for attenuation of horizontal motions, back-arcs evolution can even constrain plates and shift deformations further into their interiors. As the wave around the warp propagates, it depresses lithosphere into the amphitheatre-like shape (Fig.3), where deep troughs or subduction zones could originate (e.g. North Sulawesi), as it has been observed by Hall[19]. This topology is also clearly visible on matured subduction systems of Banda Sea[23] or Tyrrhenian Sea[24].

In many cases, supposed delamination accompanies development of the structure. At the beginning, downwarping mantle lithosphere can separate from the overlying crustal layer as it submerges downwards. The inflow of the low velocity mantle into extending space causes the crust beneath originating back-arc basins to be unusually hot (Fig.3). Lastly, at final stages, when oceanic crust of the whole basin is consumed and continental margin involved, steepening slab can delaminate again, down-flexing the crust. This mechanism would be the explanation why deep troughs originate around some back-arc basins in the late phases of their life[23].

Self-sustained subduction can be initiated, when the lithosphere is sufficiently depressed and starts falling under its own weight. Because the sinking slab from beneath the forming back-arc is not hydrated enough (ref. [25]), volcanism likely cannot occur even if the depth of 100 km is reached. Only when warping induces self-sustained subduction of the lithospheric slab, the oceanic crust becomes involved, generating fluid for melting. The process can be relatively fast due to both slab steepening (from warping) and subduction. This way an incipient roll-back, resulting from warping deformation and related extension could transform to a true roll-back[19]. Connection of volcanic arc to melting isohypse becomes relevant from this moment. Yet one question regarded the volcanism should be answered and that is whether arc advancement is caused by slab steepening or by roll-back. This finding is irrelevant to the arcs life cycle, but would be central to the question of trench migration. If volcanic arc migration is a consequence of the slab steepening, the trench alone can retreat slowly, even remain stationary. Such variant is proposed for the Banda[23] or PareceVela[12] back-arcs evolution. Dependence of the arc position on that of the trench, especially in the initial and final stages of back-arc evolution, would be so more complex than we suppose.

As this physical mechanism reveals, the lithospheric plate could warp when its movement is impeded and it would allow formation of deep marginal basins of pronounced oval or candle-flame shape. Moreover, the modelling suggests that as little as plate motion and the Earth´s surface curvature would be enough for the origin of these features. Most notable is the topological similarity of the resulting deformation to the observed back-arcs topography patterns. Although providing more examples would help to improve the model's predictions, this attempt is an initial step towards the verification of the observed relationship. Of interest is the ability of this concept to address not only problems of back-arc basins evolution, but also various other connected issues. Such way the subduction roll-back, arc migration, tectonic extension and the development of the back-arc basin would become the integral parts of one universal mechanism, which gives this model a far reaching potential.

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Methods

Constructing the thin shell finite element model. Finite element modelling of the presented problem involves establishing a shell solid of variable thickness, to which appropriate load and constraints are assigned. FEMAP software environment has been utilized to enable fast analysis modifications. Preparation of the model starts from the shell construction. Next, constraints are defined along sides of the body and the governing load. After meshing the shell, analysis is run in the solver module. All modeling operations should be performed in cylindrical coordinates (R, T, Z). The resulting 3D visualization has a wide range of options in scaling, coloring, animation and other post processing. For the purposes of this study, elementary shell surface with medium dimensions has been constructed by revolving a one meter long line. The shell's width is approximately one fifth of the cylinder circumference with narrow (5°) middle segment (Supplementary Fig. 1). The material of the shell is given the Young's modulus (5×10^{10} Pa) and Poisson's ratio (0.25). For basic analysis, these mechanical parameters are sufficient to define it. Property of the model is chosen as plate element with thickness 10 mm and 20 mm respectively. Subsequently, unit load per length (1 Nm^{-1}) is applied on one side of the shell. Next, establishing the right set of constraints and their configuration has a significant impact on the experiment. Two sides of the model (parallel with load) must be constrained against translation in T direction and also against rotations in R and Z (Extended Data Fig.1, label 246 triangles). Other sides (perpendicular to load) are constrained against translation in R (Extended Data Fig. 1, label 1 triangles), middle segment (the support of the whole model) against all translations and rotations (Extended Data Fig. 1, label 123 triangles). Meshing of the prepared object takes place with program default settings. Final computing is performed as Static. Resulting deformed mesh can be further scaled and covered with various contour types to show the specific features of deformation.

Preparing of model outputs for the process visualization. The images in Fig. 2a,b,c represent three snapshots of deformation taken from program animation (Supplementary Video 1) combined with appropriate cut projections. There are 18 separate steps of animation from the start of the simulated back-arc basin development. The first image is taken approximately in one third of its evolution, second in a half and final in the end, when extension already stopped. Cutting plane is situated in parallel to the original shell surface and approximately in 1/6 of the deformation depth. The outline of the cut is than raised to the surface level, what demonstrates the position of the volcanic arc (black rings in Fig. 2a,b,c).

Supplementary Video 1 shows deformation of a 10mm thick shell as it progresses in time. One square finite element is of 10x10mm in size. Color scale from the light blue to dark blue represents the increasing membrane force which is the highest in the vicinity of the model support. In that place the high strain persists after the process already slowed significantly. The Supplementary Video 2 animates a deformation of the shell with 20mm thickness.

It is of note that the model construction and methods are an innovative developments, different from standard modelling of back-arc related extension through slab roll-back. However, the main advancement of this method is the inherent integration of the plates curvature into the model.

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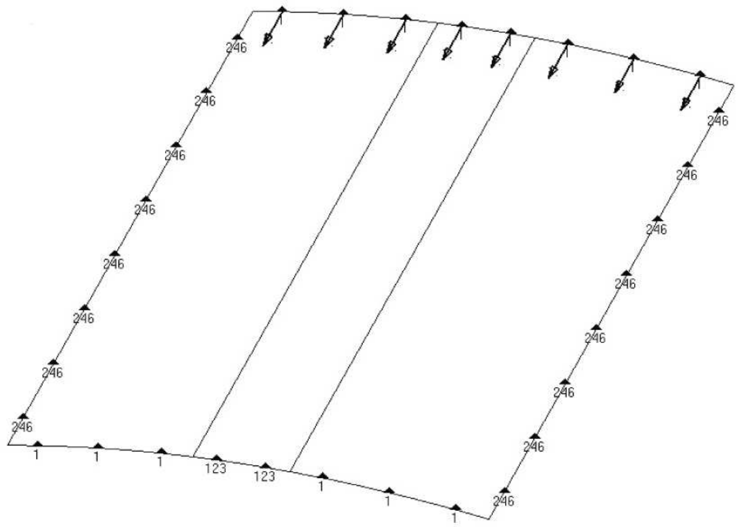
Author contributions. Peter Orvoš made the models and wrote the text.

Competing interests: Author declares no competing interests.

Code availability: The FEMAP software has been used to model the presented results. Trial version of software can be obtained from https://www.plm.automation.siemens.com/store/en-us/trial/femap.html



Extended Data Fig. 1. Thin shell construction and modelling variables. Arrows represent applied load, triangles constraints (see Methods)

Supplementary Video 1. Animation of thin shell deformation, 10 mm thickness.

Supplementary Video 2. Animation of thin shell deformation, 20 mm thickness.

Supplementary Video 3. Animation of thin shell deformation with horizontal clipping plane, 10 mm thickness.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryVideo3.mp4
- SupplementaryVideo2.mp4
- SupplementaryVideo1.mp4