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LITHOSPHERIC MODELING OF THE ORDOVICIAN FORELAND BASIN IN THE PUNA OF NW ARGENTINA: PRELIMINARY RESULTS

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ABSTRACT. The Ordovician basin in the Puna of NW Argentina developed from a back-arc to a foreland basin setting during Early and Middle Ordovician times. The transition from extensionally-related subsidence to that driven by crustal down flexure was interpreted from the temporal and spatial distribution of predominantly marine volcanoclastic facies and the tectonic subsidence pattern within the basin. This was taken to reflect a Middle Ordovician eastward thrusting of the now extinct Early Ordovician arc over part of its back-arc basin in the course of the collision of an allochthonous terrane (Laurentia?) with the South American margin. Preliminary results obtained from an infinite beam elastic plate loading model are here presented. Using the constraints of the field data, the Puna basin is modeled as resulting entirely from the effects of lithospheric loading. Two loading events, one in the Arenig, and one in the Llanvirn, with thrust sheet thicknesses of 6000 and 2000 m, respectively, best explain the observed basin geometry. The onlap patterns on the distal margin, reflecting the flexural bulge, are reproduced well using a flexural rigidity of 10^{22} Nm for the loaded plate; this represents an equivalent elastic thickness of 14 km. Higher values for the flexural rigidity are considered unlikely, as they result in an enhanced flexural bulge which uplifts marine near shore deposits on the distal margin to unrealistic subaereal positions. The quantitative test of the original field data based qualitative interpretation reproduces well salient features of the Ordovician basin in the Puna of NW Argentina. It emphasises the usefulness of combining data obtained in outcrop with numerical models.

INTRODUCTION

Outcrops of Ordovician sedimentary and volcanic rocks cover large areas in the Cordillera Oriental and the Puna of NW Argentina (Fig. 1). In the Cordillera Oriental, the Santa Victoria Group (Tremadoc-Early Llanvirn) consists of shallow marine mature sandstones and shales, overlying the Late Cambrian quartz-sandstones of the Mesón Group above an erosional unconformity (Turner, 1960). The rocks of the Santa Victoria Group are rich in trilobites, graptolites and brachiopods and were deposited predominantly under shallow subtidal and intertidal conditions. Towards the top in the late Arenig part of the succession, erosional unconformities reflecting relatively short breaks in deposition increase in abundance (Moya 1988). The region of the Cordillera Oriental emerged in the Early Llanvirn, leading to the establishment of different faunal subprovinces E and W of it during the remainder of the Middle Ordovician, and in the Late Ordovician (Salfity *et al.*, 1984).

In the eastern part of the Puna, sedimentation started in the Tremadoc with deposition of quartz-sandstones above mid-Cambrian granites or Late Proterozoic-Early Cambrian metaturbidites folded during the mid-Cambrian Pampean Orogeny. The quartz-sandstones grade into quartz-rich turbidites in the Arenig. There is no proof of post-Arenig Ordovician rocks in this part of the Puna (Schwab, 1973; Bahlburg *et al.*, 1990). In the western Puna, the record starts in the Arenig with a c. 3500 m thick volcanoclastic succession (Aguada de la Perdiz Formation, Garcia *et al.*, 1962) representing a volcanoclastic apron of a partly subaerial volcanic arc active only in the Early Ordovician (Koukharsky *et al.*, 1988; Breitkreuz *et al.*, 1989; Bahlburg, 1990). There is no record of active volcanism after the Arenig. The volcanoclastic apron reflects a marked deepening of the depositional site from vesicular basic lavas associated with stromatolites formed at sea-level at its base to tuffs and increasingly fine-grained purely volcanoclastic turbidites at the top. Although this succession is dated by graptolites, no true paleobathymetric indicators are available above the stromatolite horizons (Coira and Barber, 1987; Bahlburg *et al.*, 1990). The volcanoclastic apron is overlain by the Puna Turbidite Complex (c. 3500 m) consisting of two turbidite systems of Llanvirn and Llandeilo age, respectively, as dated by graptolites (Bahlburg, 1990; 1991; Bahlburg *et al.*, 1990; Calalaste Group, Aceñolaza and Baldis, 1987). The rocks of the turbidite complex are strongly volcanoclastic but contain minor amounts of metasedimentary detritus. Fragments of basic volcanic rocks decrease in abundance through time in favor of those of more silicic composition.

In modification of earlier subduction models for the Andean margin in the Ordovician (Coira *et al.*, 1982; Hervé *et al.*, 1987), the evolution of the Puna basin was interpreted as connected to the collision of the Arequipa Terrane (Ramos, 1988; Palma, 1990; Forsythe *et al.*, 1993), leading to the Early Ordovician arc being thrust eastward over its back-arc basin. This caused tectonic subsidence rates of up to 600 m/Ma associated with high sedimentation rates in the developing foreland basin (Fig. 2; Bahlburg, 1990; Bahlburg *et al.*, in press).

According to the recently revived hypothesis of the Late Proterozoic supercontinent (Bond *et al.*, 1984; Dalziel, 1991), eastern Laurentia rifted away from western South America at the end of the Proterozoic. The two collided again, with Laurentia in a more northerly position, during the Oclóyic

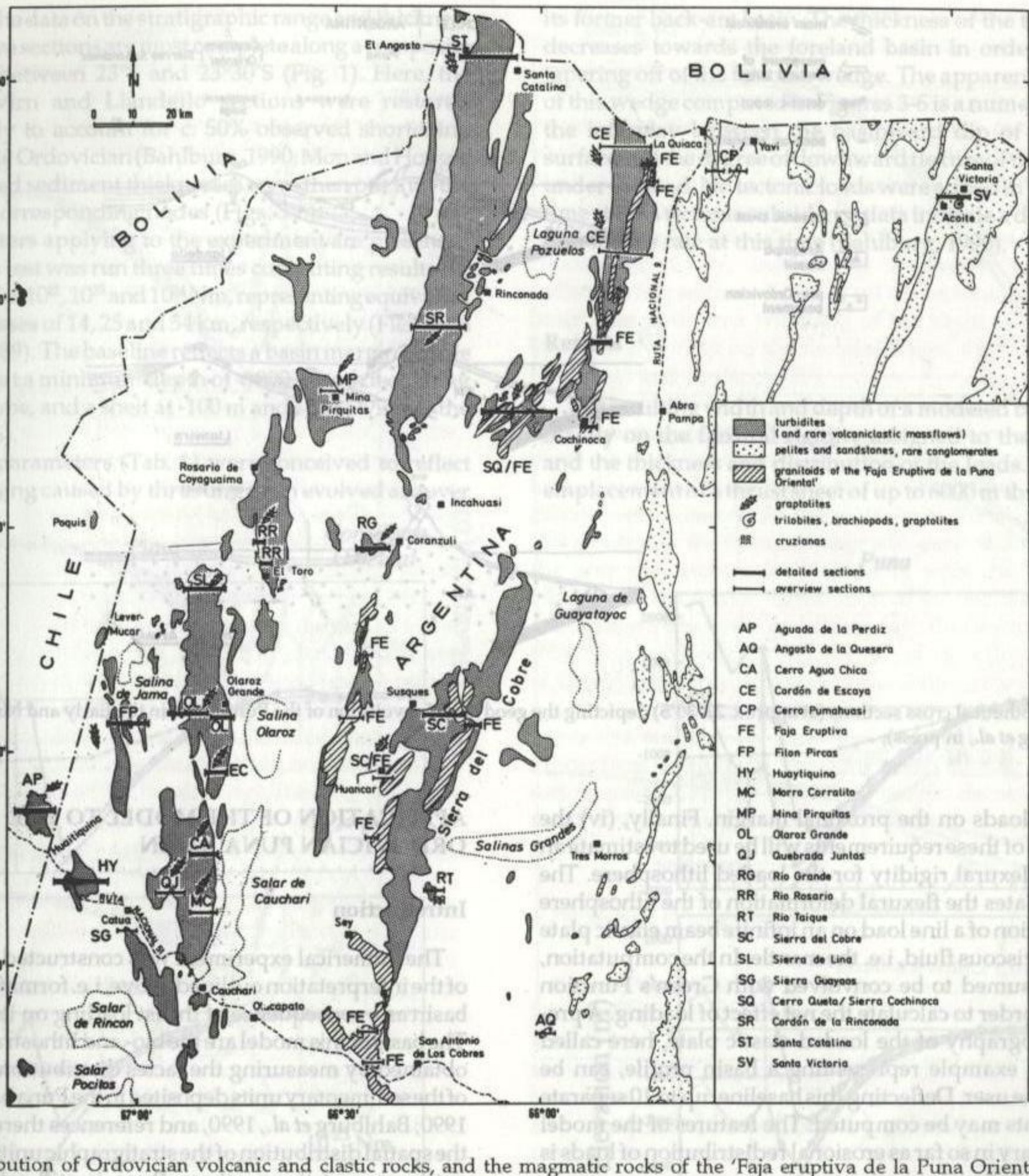

Figura 1: Distribution of Ordovician volcanic and clastic rocks, and the magmatic rocks of the 'Faja eruptiva de la Puna Oriental', in the NW Argentinian Puna and parts of the Cordillera Oriental. Black bars indicate locations of measured sections (from Bahlburg, 1990). EC: Esquina Colorada.

orogeny in the late Ordovician (Dalla Salda *et al.*, 1992). This may be reflected in NW Argentina by the Late Cambrian-Early Ordovician potential rift-to-drift succession in the Argentinian Cordillera Oriental represented by the Mesón and Santa Victoria Groups (see above). Consequently it would be likely that a passive margin stage in the Late Cambrian and possibly Tremadoc preceded the development of a destructive margin stage in the Arenig.

In order to test this hypothesis and the field data based model of Bahlburg (1990, 1991) and Bahlburg and Breitkreuz (1991), a lithospheric loading model was developed which should be able to take account of 1st order features observed in the evolution of the Ordovician Puna basin in NW Argentina. Preliminary results of this test are presented in this paper.

Properties of the Model

Numerical details of the model will be discussed in Bahlburg and Furlong (in prep.). The model has to fulfill the following requirements. (i) It has to be able to combine theoretically derived data on imposed (tectonic) load properties with sedimentological data observed in the field, i.e. distribution and thickness of sedimentary units. (ii) Tectonic loads should create a basin wide and deep enough to accomodate observed marine sediment thicknesses (sedimentary loads) below sea-level. (iii) Basin configuration and thus tectonic load thicknesses in combination with sedimentary loads have to reproduce observed shoreline positions especially on the distant margin of the basin, i.e on the flexural bulge, as it responds most sensitively to any change in the properties of

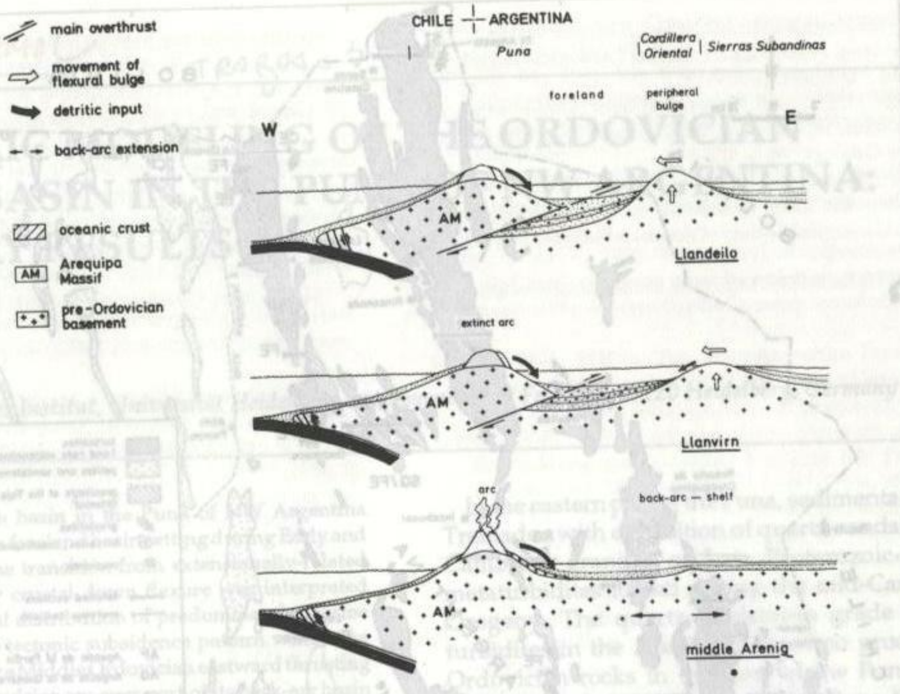

Figura 2: Hypothetical cross sections (at approx. 23°30'S) depicting the geodynamic evolution of the Puna basin in the Early and Middle Ordovician (from Bahlburg *et al.*, in press).

the tectonic loads on the proximal margin. Finally, (iv) the combination of these requirements will be used to estimate an appropriate flexural rigidity for the loaded lithosphere. The model calculates the flexural deformation of the lithosphere after imposition of a line load on an infinite beam elastic plate overlying a viscous fluid, i.e. the mantle. In the computation, loads are assumed to be convolved with Green's Function response in order to calculate the net effect of loading. A pre-existing topography of the loaded elastic plate, here called baseline, for example representing a basin profile, can be defined by the user. Deflecting this baseline, up to 10 separate loading events may be computed. The features of the model are preliminary in so far as erosional redistribution of loads is not yet included.

APPLICATION OF THE MODEL TO THE ORDOVICIAN PUNA BASIN

Introduction

The numerical experiment was constructed along the lines of the interpretation outlined above, i.e. formation of the Puna basin as a consequence of thrust loading on its western side. The basis of this model are the bio- and lithostratigraphic data obtained by measuring the facies distribution and thickness of the sedimentary units deposited in the Puna basin (Bahlburg, 1990; Bahlburg *et al.*, 1990, and references therein). However, the spatial distribution of the stratigraphic units regarding the entire area of the northern Puna is still relatively poorly

	Flexural Rigidity* (Nm)	Density of the Mantle (kg/m³)	Density of the Crust (kg/m³)	Thickness of Tectonic Loads (m)	Density of Tectonic Loads (kg/m3)	Thickness of Sedimentary Loads (m)	Density of Sedimentary Loads (kg/m3)	Width of Loads (m)
Arenig	10^{22}-10^{24}	3300	2800	max. 6000	2800	3500 - 0	2500	15000
Llanvirn	10^{22}-10^{24}	3300	2800	max. 2000	2800	2700 - 0	2500	15000
Llandeilo	10^{22}-10^{24}	3300	2800	0	2800	900 - 0	2500	15000

*: constant in any given model run

Tabla 1: Input parameters used in the lithospheric loading model. Tectonic loads: loads emplaced as a thrust wedge on the western side of the basin (left side of Figs. 4, 5 and 7). Sedimentary loads: loads represented by the sediments deposited in the basin. Width of loads: horizontal width of the respective tectonic and sedimentary load increments used in the model.

constrained. The data on the stratigraphic range and thickness of the respective sections are most complete along a composite W-E transect between 23°S and 23°30'S (Fig. 1). Here, the Arenig, Llanvirn and Llandeilo sections were restored palinspastically to account for c. 50% observed shortening after the Middle Ordovician (Bahlburg, 1990; Mon and Hongn, 1991). Measured sediment thicknesses were then put into the model at the corresponding nodes (Figs. 3-6).

The parameters applying to the experiment are presented in Table 1. The test was run three times computing results for flexural rigidities 10^{22}, 10^{23} and 10^{24} Nm, representing equivalent elastic thicknesses of 14, 25 and 54 km, respectively (Flemings and Jordan, 1989). The baseline reflects a basin margin profile with the basin at a minimum depth of -1000 m and deepening to the left, a slope, and a shelf at -100 m and shallowing to the right (Figs. 3-6).

The model parameters (Tab. 1) were conceived to reflect crustal thickening caused by thrusting of an evolved arc over its former back-arc basin. The thickness of the tectonic loads decreases towards the foreland basin in order to reflect a tapering off of the tectonic wedge. The apparent topography of this wedge computed in Figures 3-6 is a numerical result of the interplay between the basinward dip of the wedge's surface and the degree of downward flexure of the lithosphere under the load. No tectonic loads were added in the Llandeilo time step as tectonic subsidence data indicate a decrease in the subsidence rate at this time (Bahlburg, 1990).

Results

The resulting width and depth of a modeled basin depends mainly on the flexural rigidity assigned to the lithosphere, and the thickness and distribution of the loads. Through the emplacement of a thrust sheet of up to 6000 m thickness in the

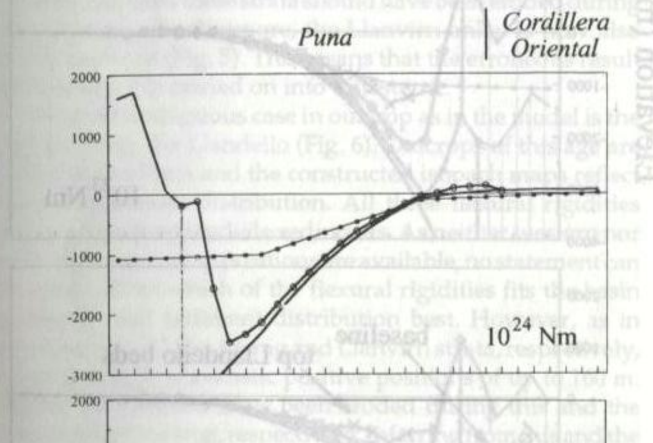

Figura 3: Results of times step 1 'Arenig' (for input parameters see Table 1). Values of the flexural rigidity are 10^{22}, 10^{23} and 10^{24} Nm, representing equivalent elastic thicknesses of 14, 25 to 54 km (Flemings and Jordan, 1989).

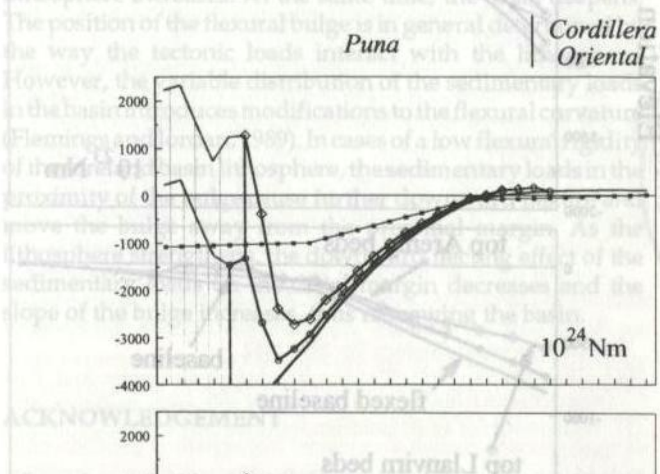

Figura 4: Results of time step 2 'Llanvirn' (for input parameters see Table 1).

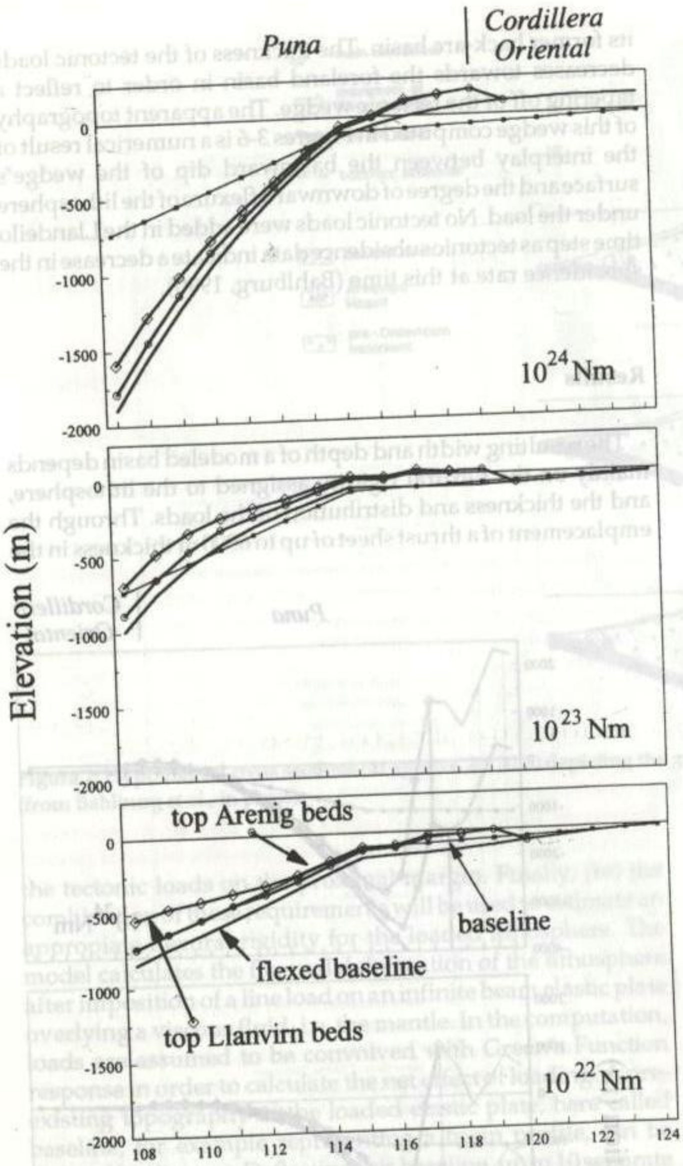

Figura 5: Onlap pattern on the flexural bulge after timestep 2. Note the unrealistic position above sea-level of the marine Arenig and Llanvirn strata in the cases of the flexural rigidities 10^{23} and 10^{24} Nm of the loaded lithosphere.

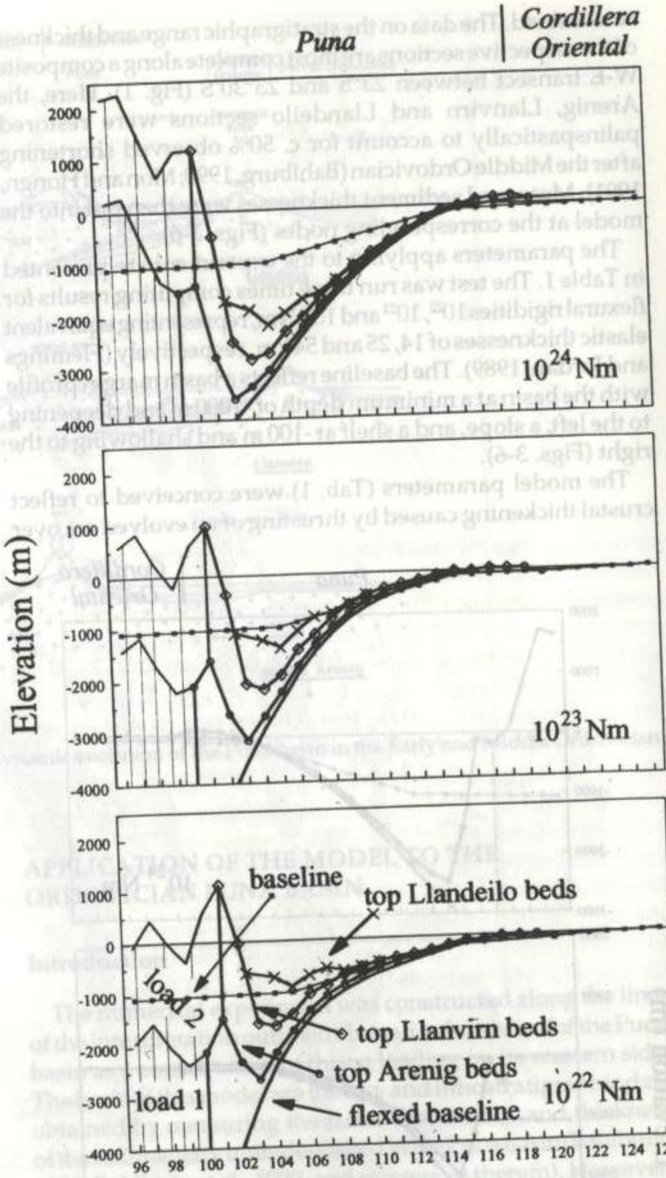

Figura 6: Results of time step 3 'Llandeilo' (for input parameters see Table 1).

Arenig, and an additional thrust sheet of 2000 m thickness in the Llanvirn (Tab. 1), a basin of c. 300 km width is created in the model, corresponding to the palinspastically restored width of the basin. In the 1st timestep, the Arenig (Fig. 3), the model fulfills the requirements outlined above in a general way for the cases of a flexural rigidities of 10^{22} and 10^{23} Nm. In the former case, all sediment in the basin resulted in being marine, except for one node close to the tip of the load. At this node the HY-section (Fig. 1) is put into the model with it's measured thickness of 3500 m. Accomodation space may have been created here in addition to the effect of flexure by faults not accounted for in the model. Furthermore, new biostratigraphical data presented by Moya et al. (this congress) point to the possibility that the lower part of the HY-section is Tremadoc in age. The thickness used for the Arenig model run could therefore be exaggerated. An additional complication results from the extensive Cenozoic volcanic cover present in this area which obscures the spatial facies relationships at the western margin of the Ordovician basin.

However, as the most sensitive feature the shoreline at the distal margin on the flexural bulge in the Cordillera Oriental is in its appropiate position at node 120. In the latter case, the shoreline is located at node 117, reflecting a basinward shift of c. 45 km. The marine deposits beyond node 117 were deposited up to 12 m above base-level. For a flexural rigidity of 10^{24} Nm, the eastern coastline is shifted basinward by 4 nodes equalling 60 km. This results in the marine Arenig beds being computed in an uplifted subaerial position of up to 140 m. In the second and third case, the respective Arenig strata should not have been deposited at all.

If timestep 2 (Llanvirn, Fig. 4) is added to timestep 1, a similar picture results. Mimicking the emplacement of a 2nd thrust sheet (load 2, Fig. 4), the tectonic loads extend further east by one node, i.e. 15 km. A flexural rigiditiy of 10^{22} Nm fulfills the requirements in principle, the shoreline on the distal margin is in the correct position (Figs. 4, 5). In the remaining cases the observed coastal onlap position of the Llanvirn strata is shifted downslope by 3 to 4 nodes, and the observedly marine Arenig strata close to the eastern basin margin are now upliftet to over 130 m. Realistically, as uplifted deposits these strata should have been eroded during this timestep. Furthermore, the Llanvirn onlap is now also above sea level (Fig. 5). This means that the erroneous result of timestep 1 is carried on into timestep 2.

The most ambiguous case in outcrop as in the model is the 3rd timestep, the Llandeilo (Fig. 6). Outcrops of this age are scarce in the Puna and the constructed isopach maps reflect only a minimum distribution. All three flexural rigidities accomodate the Llandeilo sediments. As neither western nor eastern coastal onlap positions are available, no statement can be made about which of the flexural rigidities fits the basin geometry and sediment distribution best. However, as in timestep 1 and 2 the Arenig and Llanvirn strata, respectively, again reside in unrealistic positive positions of up to 160 m. Again, they should have been eroded during this and the preceeding time step, respectively. Inferring from this and the results of timesteps 1 and 2, a flexural rigidity of 10^{22} Nm appears to be the most realistic value. Especially the 10^{24} Nm model runs produce basins which still have an up to 3 km deep water column above the top sedimentary surface although a considerable amount of sediment has alrerady been deposited. Furthermore, the tectonic loads stick out up to 4 km creating an unrealistically steep relief over very short distances. Even though the rocks deposited in the basin are dominantly turbidites, and in view of the absence of paleobathymeytric indicators, there is still no need to assume exceedingly high depositional depths. The model setup requires that the thrust arc overrides an attenuated back-arc crust, thus implying a lower flexural rigidity. For these considerations, the assignment of a flexural rigidity of 10^{22} Nm to the Puna basin is favoured.

INTERPRETATION

The presented preliminary results of the lithospheric loading model demonstrate it's ability to reproduce the overall geometry and sediment distribution of the Ordovician Basin in the Puna of NW Argentina. They show that the basin's development conformed to physical parameters of foreland basin dynamics. Although the model results are non-unique (Bahlburg & Furlong, in prep.), they support the interpretation that the basin evolved from a back-arc to a foreland setting (Fig. 2; Bahlburg, 1990, 1991).

More generalised conclusions concerning the geometry of foreland basins may be derived from the model. If only variations in the flexural rigidity are considered, a foreland basin widens as the flexural rigidity of the lithosphere on which it resides increases (e.g. Beaumont *et al.*, 1982; Huntoon and Furlong, 1987; Sinclair *et al.*, 1991). In cases of a constant flexural rigidity, increasing transport coefficients redistributing sediment eroded off the tectonic loads into the basin also result in a widening of the basin as the deposits increasingly onlap on the flexural bulge, thus depressing it (Flemings and Jordan, 1989).

This study shows that, everything else remaining constant, an increase in flexural rigidity may result in a decrease of basin width. Within each timestep, the considered model basin decreases in width by c. 60 km while the strength of the lithosphere increases. At the same time, the basin deepens. The position of the flexural bulge is in general determined by the way the tectonic loads interact with the lithosphere. However, the variable distribution of the sedimentary loads in the basin introduces modifications to the flexural curvature (Flemings and Jordan, 1989). In cases of a low flexural rigidity of the foreland basin lithosphere, the sedimentary loads in the proximity of the bulge cause further downward flexure and move the bulge away from the proximal margin. As the lithosphere strengthens, the downward flecting effect of the sedimentary loads on the distal margin decreases and the slope of the bulge increases, thus narrowing the basin.

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