Mountain belt growth inferred from histories of past plate convergence: A new tectonic inverse problem

Iaffaldano, Giampiero; Bunge, Hans-Peter; Buecker, Martin

Published in:
Earth and Planetary Science Letters

DOI:
10.1016/j.epsl.2007.06.006

Publication date:
2007

Document version
Early version, also known as pre-print

Citation for published version (APA):
Iaffaldano, G., Bunge, H-P., & Buecker, M. (2007). Mountain belt growth inferred from histories of past plate convergence: A new tectonic inverse problem. *Earth and Planetary Science Letters*, *260*(3-4), 516-523. https://doi.org/10.1016/j.epsl.2007.06.006

Available online at www.sciencedirect.com
ScienceDirect
Earth and Planetary Science Letters 260 (2007) 516–523
EPSL
www.elsevier.com/locate/epsl

Mountain belt growth inferred from histories of past plate convergence: A new tectonic inverse problem

Giampiero Iaffaldano [a,*], Hans-Peter Bunge [a], Martin Bücker [b]

[a] *Geophysics Section, Department of Geo-and Environmental Sciences, Ludwig-Maximilians, University, Munich — Germany*
[b] *Institute for scientific computing, RWTH Aachen University, Aachen — Germany*

Received 9 March 2007; received in revised form 28 May 2007; accepted 3 June 2007
Available online 12 June 2007
Editor: G.D. Price

Abstract

Past plate motions display a range of variability, including speedups and slowdowns that cannot easily be attributed to changes in mantle related driving forces. One key controlling factor for these variations is the surface topography at convergent margins, as previous modeling shows that the topographic load of large mountain belts consumes a significant amount of the driving forces available for plate tectonics by increasing frictional forces between downgoing and overriding plates. Here we use this insight to pose a new tectonic inverse problem and to infer the growth of mountain belts from a record of past plate convergence. We introduce the automatic differentiation method, which is a technique to produce derivative code free of truncation error by source transformation of the forward model. We apply the method to a publicly available global tectonic thin-shell model and generate a simple derivative code to relate Nazca/South America plate convergence to gross topography of the Andes mountain belt. We test the code in a search algorithm to infer an optimal paleotopography of the Andes 3.2 m.y. ago from the well-known history of Nazca/South America plate convergence. Our modeling results are in excellent agreement with published estimates of Andean paleotopography and support the notion of strong feedback between mountain belt growth and plate convergence.

Keywords: plate convergence; mountain building; numerical inversion; Andean paleotopography

1. Introduction

Computer models of the lithosphere are a powerful tool in tectonics. They allow us to identify key controlling parameters from forward simulations and to constrain their values through an inverse modeling approach. One potentially important parameter in regulating the velocity of tectonic plates is the topography of large mountain belts along their margins. At the Nazca/South America (NZ/SA) plate boundary, for example, recent tectonic simulations show a 30% reduction in plate convergence following the Miocene/Pliocene uplift of the Puna and Altiplano plateaus (Iaffaldano et al., 2006). The simulations link the velocity reduction explicitly to frictional forces along the brittle portion of the plate boundary arising from the overburden pressure of the newly raised topography. They are in excellent agreement with paleomagnetic and geodetic measures of NZ/SA plate convergence. The recent reduction in NZ/SA convergent rate is not an

* Corresponding author.
E-mail address: giampiero@geophysik.uni-muenchen.de (G. Iaffaldano).

0012-821X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2007.06.006

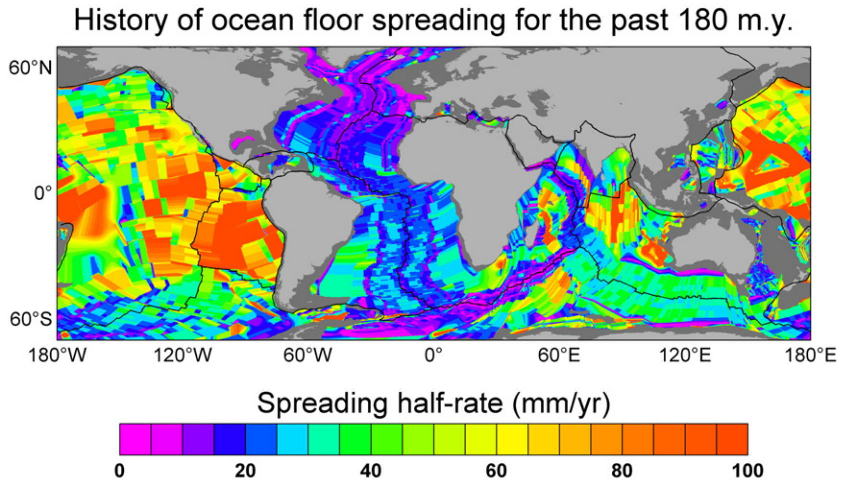

Fig. 1. Spreading half-rates for the past 180 m.y. after a recent global compilation by Whittaker and Müller. Abrupt changes in global spreading rates reveal short-term variations in plate motions. These are probably not due to changes in mantle driving forces, which occur on a much longer time scale of the order of 50 to 100 m.y. as indicated by global mantle circulation models (see text), and are likely related to short-term variations in plate boundary forces caused, for example, by rapid variations in surface topography at convergent margins. Global plate boundaries are in black, continental lithosphere in light gray.

isolated episode of a rapid change in plate motion. In fact, such changes are well documented from detailed paleomagnetic reconstructions of oceanic spreading rates. Fig. 1 shows a recent compilation of global sea floor spreading half-rates (Whittaker and Müller, 2006). It is evident that the record is characterized by a number of abrupt variations in plate velocities throughout the past 180 m.y. Moreover, the global positioning system (GPS) now allows us to derive precise estimates of present-day motions (Dixon, 1991). Such measurements reveal a number of plate motion changes even on relatively short time-scales, on the order of a few m.y. This is evident from Fig. 2, where we compare global plate motions over the past 3.2 m.y. from the paleomagnetic reconstruction NUVEL-1A (DeMets et al., 1994) relative to the geodetic compilation REVEL (Sella et al., 2002). Fig. 2 reveals significant plate motion change, for example for the India, Nazca, and South America plates, over the past 3.2 m.y. Those variations cannot easily be attributed to changes in mantle related driving forces,

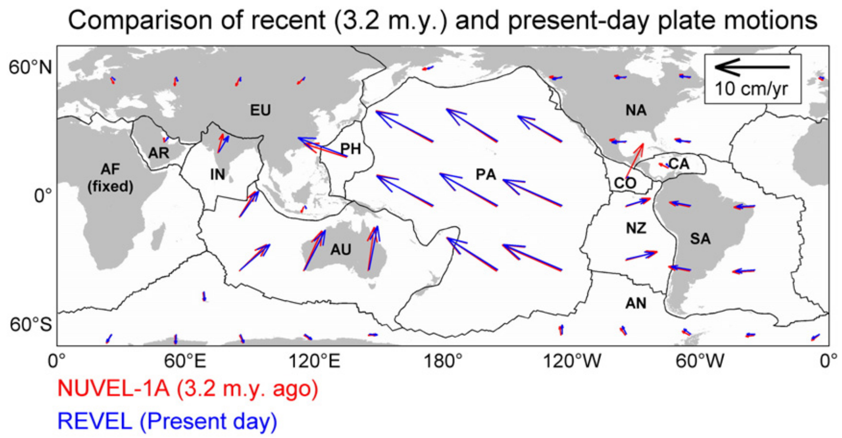

Fig. 2. Comparison of plate motion models over the past 3.2 m.y. derived from paleomagnetic (NUVEL-1A, in red) observations with instantaneous geodetic (REVEL, in blue) estimates. Global plate motions reveal significant short-term variations even for the most recent plate motion history, which are unlikely related to changes in mantle driving forces and most probably due to plate boundary forces. There are significant directional changes for the India (IN) plate, as well as changes in the magnitude of motion for Nazca (NZ) and South America (SA) plates. Velocity vectors are plotted in a reference frame fixed with rigid Africa (AF) plate. Plate boundaries are in black, continents are in gray. Plate abbreviations: AN—Antarctica, AR—Arabia, AU—Australia, CA—Carribean, CO—Cocos, EU—Eurasia, NA—North America, PA—Pacific, PH—Philippines.

because the global mantle circulation system operates much too sluggish to vary significantly on time scales of a few million years and probably undergoes changes on a much longer time scale on the order of 100–200 m.y. (Bunge et al., 1998). A likely key controlling factor for short-term plate motion variations, however, are rapid variations in surface topography at convergent margins. This is because the topographic load of large mountain belts consumes a significant amount of the driving forces available for plate tectonics as noted above. The observation suggests to explore a novel inverse problem and to infer mountain belt paleotopography from a record of past plate convergence. Here we follow this approach and apply estimates of the NZ/SA plate convergence history to infer past topography of the Andes. The theoretical predictions are verified explicitly against a range of Andean paleotopography estimators.

Inverse problems are, of course, well known in the Earth sciences where one often must infer one set of model parameters from a related set of measurements (Tarantola, 1987; 2004). In seismology they date back more than 30 yr, when Backus and Gilbert (1968) studied the resolving power of gross earth data. In tectonic studies inverse methods are used frequently to constrain the kinematics of plate motion through the growing body of data from the global positioning system (GPS) (Bennett et al., 2004), although their use in dynamic models of the lithosphere is still in its infancy.

Inverse techniques rely on an objective function, J, which maps differences between model predictions and observables to a scalar through a sum of integrals. The necessary condition for an optimum of J, that grad $J=0$, requires the differentiation of the forward model with respect to the unknown parameters. A straightforward way to obtain grad J is through finite differencing of the forward model. Unfortunately, the method of computing model sensitivities by divided differences is prone to truncation error and involves the difficulty of determining a suitable step size to balance truncation and cancellation errors. Moreover, it consumes large amounts of computer time especially in numerical simulations involving millions of degrees of freedom. Here the use of an adjoint technique is computationally attractive (Bunge et al., 2003). But the approach requires the analytic derivation of an adjoint and manually written code. In contrast, the technique of Automatic Differentiation is a method for automatically generating programs to compute derivatives (Rall, 1981). In the Automatic Differentiation approach a computer program evaluating a function representing the forward problem is mechanically transformed into another computer program capable of evaluating the Jacobian or higher order derivatives of the function (Griewank, 2000). Automatic Differentiation exploits the fact that every computer program, no matter how complicated, executes a sequence of elementary arithmetic operations and that by applying the chain rule of derivative calculus repeatedly to these operations, derivatives of arbitrary order can be computed automatically and accurate to working precision. In addition, the automatic nature of the approach allows for straightforward integration of new physical processes and constraints into a model without need for further human intervention. This makes the method well suited for a wide range of computer simulations across the earth sciences (Bischof et al., 1996a; Sambridge et al., 2005; Rath et al., in press).

In this paper we apply the Automatic Differentiation tool ADIFOR (Bischof et al., 1996b) (see www.autodiff.org) in the so-called forward mode to a publicly available global plate tectonic model (SHELLS) (Kong and Bird, 1995). Our goal is to accurately infer an optimal paleotopography in the Andes some 3 m.y. ago that is consistent with the record of recent NZ/SA America plate convergence. An indication of the gross value of the Andean topography at the same age has in fact been inferred in a previous study (Iaffaldano et al., 2006) by applying a simple derivative-free line search. The approach presented here is emphatically not intended to explore the full capabilities of the Automatic Differentiation approach, because there are still large uncertainties associated with estimating paleotopography. Rather we wish to explore whether the sensitivity information obtained from our approach can be used successfully to constrain tectonic modeling parameters. To this end we focus our attention deliberately on a tectonic problem for which the first-order model sensitivity has been mapped from previous forward simulations, testing the hypothesis that temporal variations in plate convergence could potentially serve as a proxy for the evolution of gross topography in mountain belts.

2. Model and results

Fig. 3 shows observed Nazca plate motion relative to South America 10 m.y. ago (a) and today (b). Paleomagnetic reconstructions indicate a convergence of (10.3 ± 0.2 cm/yr) at (71.5° W, 25° S) (Gordon and Jurdy, 1986), whereas the current value obtained from geodetic data is (6.7 ± 0.2 cm/yr) at the same location (Norabuena et al., 1998), consistent with an overall velocity reduction of about 30% over the past 10 m.y. Fig. 3 also shows the result of two global plate tectonic computer simulations. The simulations are performed

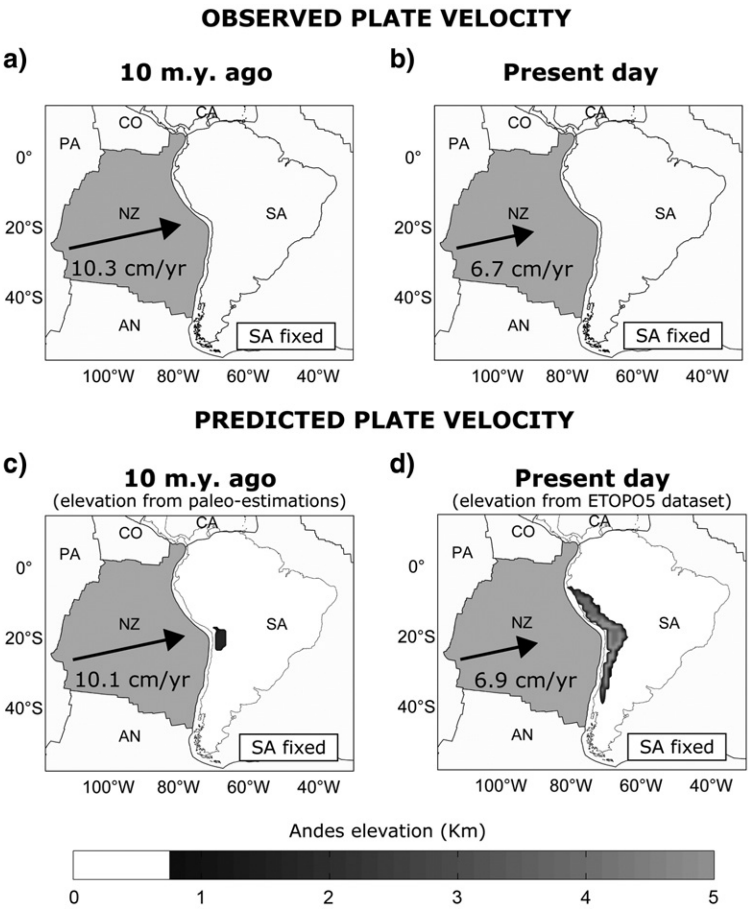

Fig. 3. Observed convergence rate between Nazca (NZ) and South America (SA) plates at (71.5° W, 25° S) 10 m.y. ago (a) and at present day (b). Observations reveal a velocity reduction of about 30% over the past 10 m.y. Computed Nazca plate motion relative to South America from global plate motion simulations corresponding to Andean paleotopography 10 m.y. ago (c) and present-day topography (d). Paleotopography 10 m.y. ago results in a computed convergence rate of 10.1 cm/yr at the same position, while present-day topography results in a convergence rate of 6.9 cm/yr. The difference implies that the deceleration of the Nazca plate is due to the topographic load of the Andes (see text). Colorscale enhances areas above 700 m altitude. Plate boundaries are in gray, coastline is in black. Plate abbreviations as in Fig. 2.

using the SHELLS code. It employs isostasy through the Airy compensation (Bird, 1998). A complete representation of lithosphere strength requires a 3-D volume approach; however for large scale tectonic problems it is reasonable to assume that the horizontal velocity component to first order is independent of depth and to use a vertical integration of lithospheric strength down to a depth consistent with the Airy compensation. Such approach reduces the 3-D problem to two dimensions (Bird, 1989), in what is known as thin-shell approximation. We account for realistic plate driving forces from global mantle circulation modeling (Bunge et al., 1998; 2002) and include topography, a temperature-dependent viscous rheology and faults along plate margins to accommodate Coulomb frictional sliding in the cold brittle portion of the lithosphere and dislocation creep in the warm ductile regions. The computed Nazca/South America convergence is 10.1 cm/yr for paleotopography corresponding to conditions 10 m.y. ago (c), whereas the current elevation of the Andes (National Geophysical Data Center, 1998) results in a computed plate convergence of 6.9 cm/yr (d). Note that the assumed change in topography of the Andes is the only difference between (c) and (d) and that it is associated with an increase of frictional resting forces along the plate margin to tectonically significant values as high as $2 * 10^{13}$ N/m (Iaffaldano et al., 2006). The modeled plate velocities agree with the recorded plate motions in (a) and (b) at the 68% confidence level.

Next to the observations from Gordon and Jurdy and Norabuena et al., there is a velocity constraint available at 3.2 m.y. on Nazca/South America plate convergence

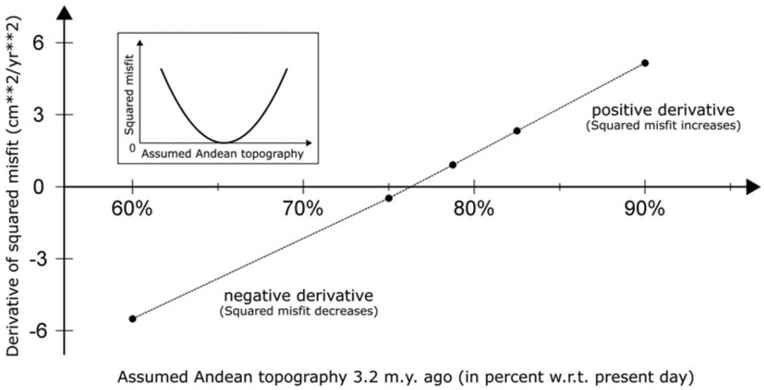

Fig. 4. AD-computed derivatives of convergence Squared misfit with respect to assumed Andean topography 3.2 m.y. ago (in percent with respect to present-day elevation). Squared misfit is defined as the squared difference between observed and modeled Nazca/South America convergence rate 3.2 m.y. ago (see text). An illustrative sketch of the Squared misfit trend with respect to assumed Andean topography 3.2 m.y. ago is shown in the inset figure. The iterative bisection search locates the zero of derivative (i.e. minimum of squared misfit) within 5 iterations in the range of 70%–80%. Thus the optimal topography corresponds to about 75% of the total topographic growth over the past 10 m.y.

from the global plate motion reconstruction NUVEL-1A. The record is based on paleomagnetic data and indicates a convergence of (8±0.2 cm/yr), faster than the current rate but slower than the convergence 10 m.y. ago. We use this constraint to perform a numerical inversion of the tectonic model. In our approach we take the ADIFOR tool to generate a derivative code of SHELLS and apply the code in an iterative bisection search to infer an optimal paleoelevation of the Andes 3.2 m.y. ago. The optimum refers to an elevation resulting in a model-predicted plate convergence that agrees with the recorded convergence rate of NUVEL-1A. Specifically we compute the derivative in the tectonic model of the Squared misfit between observed and modeled Nazca/South America plate convergence relative to Andean topography at 3.2 m.y.:

$$\text{Squared misfit}(e) = (\text{Conv\_obs} - \text{Conv\_sml}(e))^2$$

Here Conv_obs is the observed convergence from NUVEL-1A and Conv_sml(e) is the modeled convergence from SHELLS (when used to perform forward simulations) for an assumed Andean paleoelevation denoted by e. The above expression is nothing but the squared distance between the observed and modeled plate convergence and provides us with a convenient misfit function of how any given Andean paleoelevation relates to a modeled plate convergence at 3.2 m.y. We sketch the qualitative behavior of the Squared misfit in the inset of Fig. 4. Note that the Squared misfit is positive by construction and that unrealistic paleoelevations of the Andes (either too high or too low) result in large values of the Squared misfit, with an optimum leading to a zero value.

Fig. 4 shows the derivative of the Squared misfit relative to a range of assumed paleoelevations of the Andes at 3.2 m.y. It is worth to notice that we express the elevation of the Andes with one single scalar parameter which is the percentage of the local topographic growth since 10 m.y., with 0% topographic growth being the topography at 10 m.y. (Fig. 3c) and 100% topographic growth corresponding to the elevation of the Andes today (Fig. 3d) at any location. Thus, the same percentage of topographic growth will correspond to different elevations in different locations of the Andean region, depending on the present-day as well as 10 m.y. ago elevation of those locations. This is a convenient way to relate the Squared misfit to one single

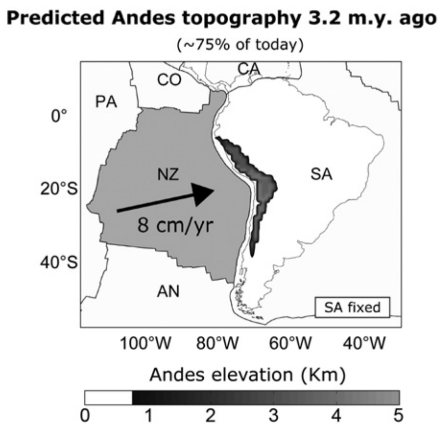

Fig. 5. Optimal Andean topography 3.2 m.y. ago inferred through AD. Optimal paleotopography results in 8 cm/yr convergence rate between the Nazca and South America plates, where the convergence velocity is consistent with the NUVEL-1A plate motion reconstruction at the 95% confidence level.

parameter representative of the whole assumed Andean topography. We note from Fig. 4 that the derivative of the Squared misfit crosses from negative to positive values in the range of 70–80% overall topographic growth and that the zero value (an optimum in the misfit function, see inset Fig. 4) occurs at about 75% of the total topographic growth. The iterative bisection search locates the optimum within 5 iterations. Thus we infer the optimal elevation of the Andes with respect to Nazca/South America plate convergence at 3.2 m.y. at about 75% of total topographic growth over the past 10 m.y. We plot this theoretical prediction of Andean paleotopography in Fig. 5.

3. Discussion

It is logical to ask whether our prediction is supported by independent estimators of paleotopography in the Andes. We address this question in Fig. 6. Here we compare our inverse modeling result with published estimates of Andean paleotopography based on paleobotanical data for the Altiplano (Fig. 6a) and Eastern Cordillera (Fig. 6b) regions (Gregory Wodzicki, 2000). We find that the predicted paleoelevation from our numerical inversion for both the Altiplano and the Eastern Cordillera at 3.2 m.y. agrees well with paleotopographic indicators to within the (admittedly wide) error range (see Fig. 6). Such results also agree with findings from forward models of NZ/SA convergent rate addresses in our previous study, where we inferred the gross Andean topography 3.2 m.y. ago by performing a derivative-free line search. Moreover, our inverse simulation supports a separate timing in the uplift history of the Eastern Cordillera relative to the Altiplano, with rapid uplift commencing somewhat later in the Eastern Cordillera than in the Altiplano. A staggered uplift activity of the Eastern Cordillera relative to the Altiplano has been suggested before (Gregory Wodzicki,

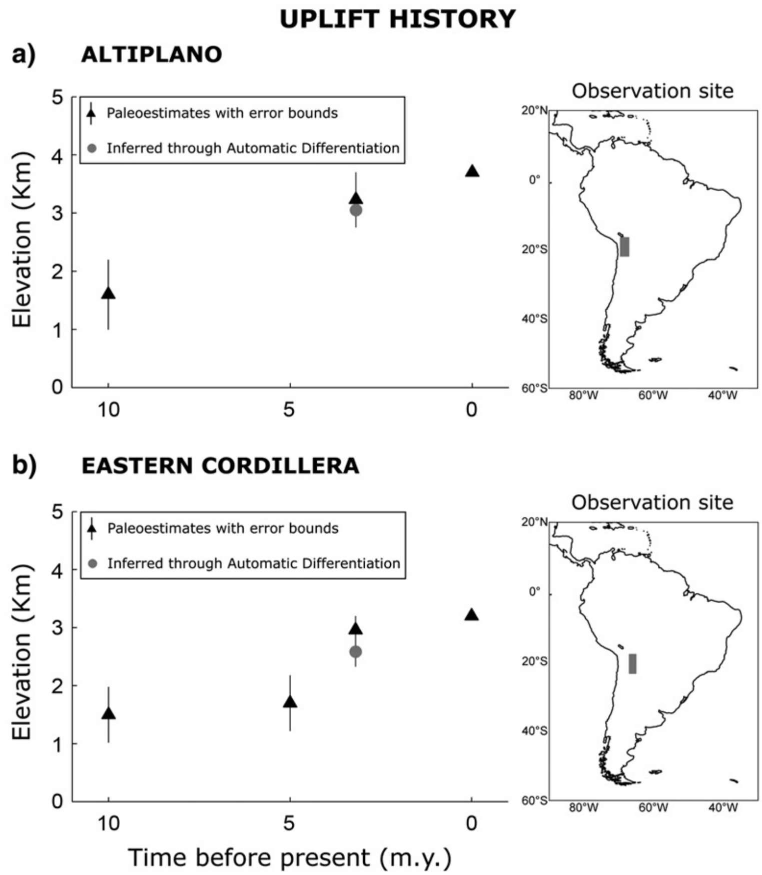

Fig. 6. Published estimates of Altiplano (a) and Eastern Cordillera (b) topography over the last 10 m.y. marked by black triangles with error bounds. AD-inferred optimal topography at 3.2 m.y. is indicated by gray dots. Optimal Andean paleotopography agrees well with independent paleotopographic estimators within the error range and supports a separate timing in the uplift of the Eastern Cordillera relative to the Altiplano, with rapid uplift commencing somewhat later in the Eastern Cordillera than in the Altiplano (see text).

2000; Ghosh et al., 2006). The Altiplano plateau, for example, had achieved less than half its present elevation 10 m.y. ago and subsequently saw an uplift of about 0.25 mm/yr during the late Miocene, reaching an elevation of about 3 km by 3.2 m.y. (Fig. 6a). The Eastern Cordillera in contrast had achieved an elevation of less than 1 km 10 m.y. ago and was uplifted primarily during the Pliocene at rates of about 0.9 mm/yr (Fig. 6b).

In our discussion we must remark upon numerical accuracy and computational cost of the Automatic Differentiation approach. The crucial advantage of this numerical technique over divided difference lies in its accuracy, which is essential to assure efficient convergence in an iterative optimization (Sinha et al., 1999). We verified that the truncation error in the value of the derivative incurred by divided differences exceeds 10% for a step size of 10^{-2}, especially near the optimum of the misfit function. The error reduces to less than a percent for smaller step sizes in the range of 10^{-3} to 10^{-7}, but increases again upon further reduction thus confirming the difficulty of finding an optimal step size for divided difference even for the relatively simple problem we consider here. In contrast, there is no truncation error in the Automatic Differentiation approach.

In our study we used AD to compute the derivative of the misfit between observed and modeled plate convergence with respect to a single model parameter, the paleoelevation of the Andes 3.2 m.y. ago.

For the derivative code we measure an execution time of 370 s, whereas the forward simulation executes in 195 s. The ratio of the execution times is 1.9, roughly comparable to numerical differentiation based on divided differences which would require two runs of the forward model. We obtain this performance without further modifying the derivative code, even though performance optimization would certainly help to improve its execution time. Thus straightforward application of the ADIFOR tool leads to a performance comparable to the fastest divided difference.

4. Conclusion

We have produced a derivative code capable of computing gradients free of truncation error by applying the AD tool ADIFOR to the publicly available thin-shell model SHELLS. The approach combines the generality of finite difference techniques and the accuracy of analytical derivatives, while at the same time eliminating `human' coding errors. We think that the technique of Automatic Differentiation has considerable potential for nonlinear optimization, linearizing of nonlinear inverse problems as well as for sensitivity analysis in tectonic computer simulations. Our model prediction of Andean paleotopography at 3.2 m.y. from records of Nazca/South America plate convergence agrees with independent paleotopographic estimators and supports the notion of strong feed back between mountain belt growth and plate convergence.

Acknowledgements

We thank two anonymous reviewers for their constructive comments. This work was supported by the Elitenetwork of Bavaria.

References

Backus, G.E., Gilbert, J.F., 1968. The resolving power of gross earth data. Geophysical Journal of the Royal Astronomical Society 16, 169–205.

Bennett, R.A., Friedrich, A.M., Furlong, K.P., 2004. Codependent histories of the San Andreas and San Jacinto fault zones from inversion of fault displacement rates. Geology 32, 961–964.

Bird, P., 1989. New finite element techniques for modeling deformation histories of continents with stratified temperature-dependent rheology. Journal of Geophysical Research 94, 3967–3990.

Bird, P., 1998. Testing hypotheses on plate-driving mechanisms with global lithosphere models including topography, thermal structure, and faults. Journal of Geophysical Research 103, 10115–10129.

Bischof, C., Pusch, G., Knoesel, R., 1996a. Sensitivity analysis of the MM5 weather model using automatic differentiation. Computers in Physics 10, 605–612.

Bischof, C., Carle, A., Khademi, P., Mauer, A., 1996b. Adifor 2.0: automatic differentiation of Fortran 77 programs. IEEE Computational Science & Engineering 3, 18–32.

Bunge, H-P., Hagelberg, C.R., Travis, B.J., 2003. Mantle circulation models with variational data-assimilation: inferring past mantle flow and structure from plate motion histories and seismic tomography. Geophysical Journal International 152, 280–301.

Bunge, H.-P., Richards, M.A., Lithgow-Bertelloni, C., Baumgardner, J.R., Grand, S., Romanowicz, B., 1998. Time scales and heterogeneous structure in geodynamic earth models. Science 280, 91–95.

Bunge, H-P., Richards, M.A., Baumgardner, J.R., 2002. Mantle circulation models with sequential data-assimilation: inferring present-day mantle structure from plate motion histories. Phil. Trans. Roy. Soc. A 360, 2545–2567.

DeMets, C., Gordon, R.G., Argus, D.F., Stein, S., 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. Geophysical Research Letters 21, 2191–2194.

Dixon, T.H., 1991. An introduction to the Global Positioning System and some geological applications. Reviews of Geophysics 29, 249–276.

Ghosh, P., Garzione, C.N., Eiler, J.M., 2006. Rapid uplift of the Altiplano revealed through 13C–18O bonds in paleosol carbonates. Science 311, 511–515.

Gordon, R.G., Jurdy, D.M., 1986. Cenozoic global plate motions. Journal of Geophysical Research 91, 12389–12406.

Gregory Wodzicki, K.M., 2000. Uplift history of the central and northern Andes: a review. Geological Society of America Bulletin 112, 1091–1105.
Griewank, A., 2000. Evaluating Derivatives: Principles and Techniques of Algorithmic Differentiation. SIAM, Philadelphia.
Iaffaldano, G., Bunge, H.-P., Dixon, T.H., 2006. Feedback between mountain belt growth and plate convergence. Geology 34, 893–896.
Kong, X., Bird, P., 1995. SHELLS: a thin-shell program for modeling neotectonics of regional or global lithosphere with faults. Journal of Geophysical Research 100, 22129–22132.
National Geophysical Data Center, Boulder, Colorado, 1998. Data announcement 88-MGG-02: digital relief of the surface of the earth. NOAA.
Norabuena, E.O., Leffler-Griffin, L., Mao, A., Dixon, T.H., Stein, S., Sacks, I.S., Ocola, L., Ellis, M., 1998. Space geodetic observations of Nazca—South America convergence across the central Andes. Science 279, 358–362.
Rall, L.B., 1981. Automatic Differentiation: Techniques and Applications. Lecture Notes in Computer Science, vol. 120. Springer Verlag, Berlin.
Rath, V., Wolf, A., Bücker, H.M., in press. Joint three-dimensional inversion of coupled groundwater flow and heat transfer based on automatic differentiation: Sensitivity calculation, verification and synthetic examples. Geophysical Journal International.
Sambridge, M., Rickwood, P., Rawlinson, N., 2005. Automatic differentiation in geophysical inverse problems. American Geophysical Union, Fall Meeting 2005, Abstract #NG42A-02.
Sella, G.F., Dixon, T.H., Mao, A., 2002. REVEL: a model of Recent plate velocities from space geodesy. Journal of Geophysical Research 107, ETG 111–ETG 1112.
Sinha, A., Rao, B.V., Bischof, C., 1999. Nonlinear optimization model for screening multipurpose reservoir systems. Journal of Water Resources Planning and Management 125, 229–233.
Tarantola, A., 1987. A strategy for nonlinear elastic inversion of seismic-reflection data. Geophysics 52, 429-429.
Tarantola, A., 2004. Inverse Problem Theory. Methods for Model Parameter Estimation. SIAM, Philadelphia.
Whittaker, J., Müller, D., 2006. New 1-minute satellite altimetry reveals major Australian–Antarctic plate reorganization at Hawaiian-Emperor bend time. American Geophysical Union Fall Meeting.