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Intra-plate seismicity and flexural stresses in central Brazil

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[1] Explaining intra-plate seismicity is a challenging task. Different models have been proposed combining weak zones and stress concentration mechanisms. Here we propose that flexural deformation is a major factor to explain seismicity in Central Brazil. A SW-NE-oriented seismic zone between the Amazon and the São Francisco cratons coincides with high gravity anomalies, possibly due to a SW-NE belt of thin crust. The load from the high-density, shallow mantle rocks causes upper crustal compressional stresses up to 100 MPa in the 200 km wide seismic zone. Away from the central zone of horizontal compression, extensional stresses in the peripheral bulge balance the regional compression explaining the aseismic areas. Three other seismic clusters in Brazil also correlate with high gravity anomalies, suggesting that flexural deformation contributes significantly to explain mid-plate seismicity in Brazil. **Citation:** Assumpção, M., and V. Sacek (2013), Intra-plate seismicity and flexural stresses in central Brazil, *Geophys. Res. Lett.*, *40*, doi:10.1029/2012GL054144.

1. Introduction

[2] Several factors have been proposed to cause earthquakes far from the active plate boundaries, ranging from weakness zones to stress concentrations. Crustal weak zones are usually due to the last major orogeny and involve ancient rifts or failed rifts [e.g., *Johnston and Kanter*, 1990], or suture zones [e.g., *Mooney et al*., 2012]. Stress concentrations can arise from lateral density variations (e.g., *Assumpção and Araujo*, 1993], contrasts of elastic properties, or fault intersections.

[3] If lateral density variations are not isostatically compensated, large flexural stresses appears in the upper crust. Flexural stresses can be caused by ice-sheet retreat, sediment load in the continental margin, or intra-crustal loads from past geological processes [e.g., *Zoback and Richardson*, 1996]. *Calais et al*. [2010] showed that Late-Pleistocene erosion of only a few meters can produce enough flexural stresses to significantly contribute to seismicity in critically stressed areas, such as New Madrid.

[4] A major difficulty with most models for intra-plate seismicity is the fact that the same geological/structural features are also present in areas with no current seismic activity (for example, not all continental shelves are equally active, despite having similar geological structures and potentially the same sources of stress). This has contributed to the debate of whether long-term migration of intra-plate seismic zones occurs, with significant implications for seismic hazard assessment [*Stein et al*., 2009; *Calais et al*., 2010]. The recent 2011 M5.8 earthquake in Virginia, occurred in an area with no significant historical activity, was one of the largest in Central and Eastern US in the last 70 years and highlighted the importance of further studies and a more detailed comparison of intra-plate seismicity between different regions. We present the spatial distribution of seismicity in central Brazil and show that flexural stresses are an important factor to explain several seismic zones in mid-plate South America.

2. Seismicity in Central Brazil

[5] Seismicity in Central Brazil is not uniform and is concentrated in different seismic zones. The maximum observed magnitude was 6.2 mb in the Parecis basin (Figure 1). Focal depths are generally not well determined, but all cases of detailed aftershock studies showed depths shallower than about 5 km [e.g., *Barros et al*., 2009]. Thrust and strike-slip mechanisms predominate, and no clear systematic differences are observed between different seismic areas, except for a hint of more compressional events in the central area of Figure 1.

[6] The SW-NE-oriented cluster in the Tocantins foldbelt (“Goiás-Tocantins Seismic Zone”, GTSZ), between the Amazon and the São Francisco cratons (Figure 1), has been attributed to the Transbrasiliano Lineament (TBL), a continental-scale feature that can be traced even in Africa [e.g., *Fairhead and Maus*, 2003]. However, several factors cast doubt on a direct relationship with the seismicity: (a) the GTSZ is close to, but not coincident with, the TBL (Figure 1), (b) the TBL continues towards the NE beneath the Parnaíba basin but is not accompanied by seismicity (Figures 1 and 2), and (c) towards the SW, the seismicity seems to offset to the W (Figure 2), changing to a N-S trend beneath the Pantanal basin, which differs from the expected SW direction of the TBL.

[7] On the other hand, the epicentral distribution shows a remarkable correlation with high gravity anomalies (Figure 2), as noted by *Berrocal et al*. [2004] and *Soares et al*. [2006]. We used the isostatic anomalies of *Sá* [2004]. Similarly to the Free-Air gravity anomalies, positive and negative values indicate mass excess and deficiency in the lithosphere, respectively. The events are mostly confined in areas with gravity anomalies higher than about −20 mGal, forming a seismic zone about 200 km wide centered in the axis of the gravity high (Figure 2b). High isostatic anomalies indicate uncompensated excess mass causing flexural deformation of the lithosphere and compressional stresses in the upper crust. In addition, central Brazil is characterized by E-W to SE-NW

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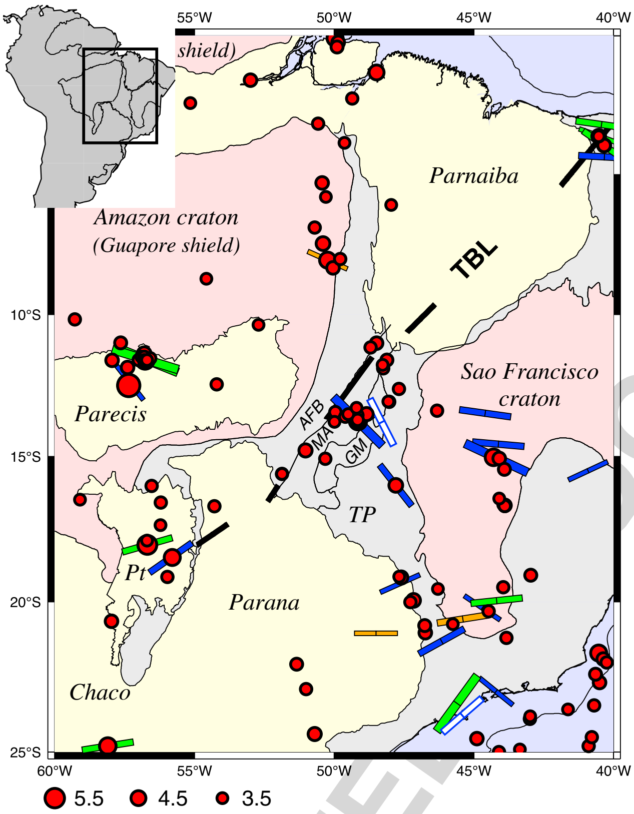

Figure 1. Main geological provinces, seismicity (red circles), and stresses. Pink areas are Archean to Paleoproterozoic cratons, gray are NeoProterozoic/Paleozoic foldbelts (such as the Tocantins Province, TP), and yellow are major Phanerozoic basins (Pt = Pantanal Basin). TBL is the TransBrasiliano Lineament. In the Tocantins Province, AFB = Araguaia foldbelt, MA = NeoProterozoic Magmatic Arc, and GM = Archean Goias Massif. Circle sizes denote magnitudes from 3.5 to 6.2. Blue, green, and orange bars are estimates of maximum horizontal stress directions (SHmax) from reverse, strike-slip, and normal faulting mechanisms, respectively, with size denoting data quality. Open blue bars are hydrofrac data.

regional compression (Figure 1), which tends to enhance the flexural compression.

3. Gravity and Stress Modeling

[8] We model the gravity anomalies in Central Brazil, assuming that the excess mass causing the isostatic anomalies is due to crustal thickness variations. The compilation of *Assumpção et al*. [2012] shows that thin crust occurs along the narrow zone of the Magmatic Arc and the Goiás Massif (Figures 3a and 3b), parallel to the gravity high. *Soares et al*. [2006] had already suggested a correlation of the GTSZ with a thin crust. We interpret the Bouguer anomalies as due simply to Moho topography (Figure 3c). A 38–40 km thick crust is seen in the west and a ~43 km thick crust in the east (accompanied by elevated topography and low Bouguer gravity). A thinned crust in the middle (an area of low elevation and high gravity) coincides with the seismic zone. The gravity data could be modeled, alternatively, with high-density intracrustal blocks, instead of Moho topography. However, the purpose of this simple model is just to estimate magnitudes of the flexural stresses in the upper crust, which do not depend critically on the location of the lithospheric load.

[9] Flexural stresses were calculated with a 2D finite element code simulating a Maxwell viscoelastic material in a state of plane strain. The numerical model has a 1600 km long by 100 km thick lithosphere containing a 40 km thick crust (Figure 4a). A non-Newtonian fluid describes the viscous behavior of the lithosphere, with the effective viscosity given by [e.g., *Grana and Richardson*, 1996]

$$\eta_{\mathrm{eff}} = \frac{\exp(Q/RT)}{2A\sigma^{(n-1)}}$$

where $Q = E_a + PV_a$ is the activation enthalpy (E_a is the activation energy, V_a is the activation volume, and P is the pressure), R is the ideal gas constant, T is the absolute temperature, A is the power law constant, σ is the deviatoric stress, and n is the power law exponent. Temperature varies linearly from the surface ($T = 0°\mathrm{C}$) to the base of the lithosphere ($T = 1300°\mathrm{C}$). For the crust, we used the rheological properties of anorthosite [*Ranalli*, 1987], which are intermediate between granite and diabase. We modeled the upper mantle as dry olivine [*Karato and Wu*, 1993]. Figure 4a shows the values used in our model. Young's modulus (E) and Poisson's ratio (ν) were assumed constant throughout the lithosphere (Figure 4a).

[10] Density loads were applied to the lithosphere according to the density contrasts of the model in Figure 3c. We also imposed a topographic load (Figure 3c) on top of the model, with 2700 kg/m^3. The density of the lithosphere increases from top to bottom (Figure 4a). The topographic and density anomalies are supported by the lithospheric strength and by isostasy.

[11] The regional stress field was simulated imposing a horizontal deformation in the onset of the simulation corresponding to a compressional stress of 30 MPa, based

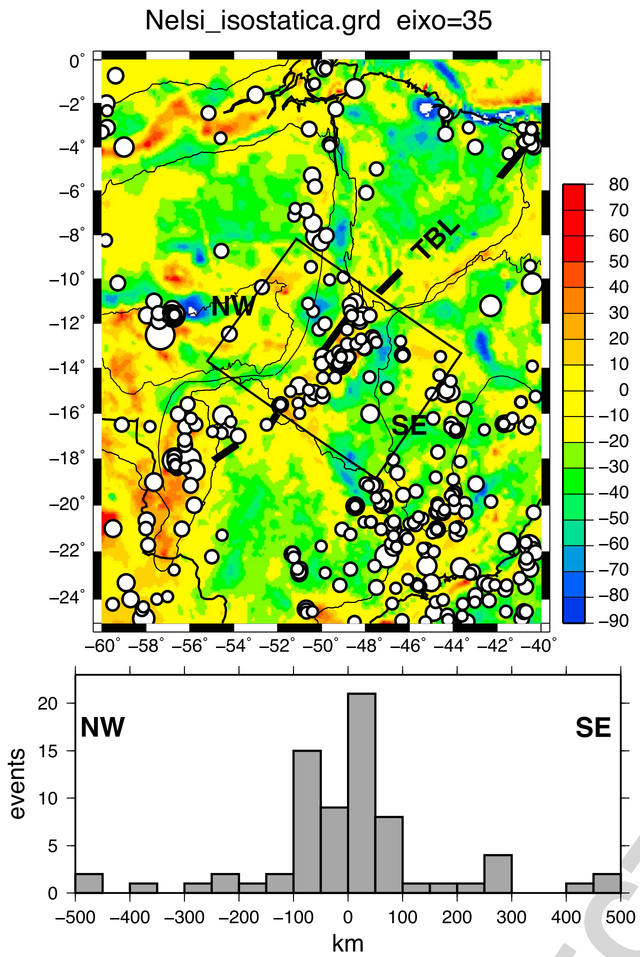

Figure 2. (Top) Isostatic gravity anomalies (color scale in mGal, from *Sá* [2004]) and seismicity. Epicenters (white circles, Brazilian catalog) have magnitudes ≥ 3.0. Solid lines are geological boundaries as in Figure 1.The rectangle is the area used to project the epicenters on a NW-SE direction. (Bottom) Histogram of the number of epicenters along the NW-SE direction. Origin ("0 km") is the SW-NE line parallel to the high gravity trend.

on stress estimates by *Coblentz and Richardson* [1996] and *Lithgow-Bertelloni and Guynn* [2004]. In the beginning of the simulation, the entire lithosphere behaves as an elastic layer supporting the topographic and density loads. However, the viscous flow modifies the stress field in the lithosphere through time concentrating stress in the upper crust and uppermost mantle. Stresses concentrate in the upper portion of the lithosphere faster during the first few million years of simulation, and gradually, the strain rate diminishes through time. Figure 4b shows the non-lithostatic stress field after 100 Myr of simulation. Given the large uncertainties in the rheological parameters, we also tried a granite rheology for the crust [*Ranalli*, 1987]. Stresses in the lower crust decrease more rapidly, but the area of high stresses in the upper crust remains essentially the same.

4. Discussion and Conclusions

[12] The modeling results (Figure 4b) show large compressional stresses in the upper crust (up to 50–100 MPa)

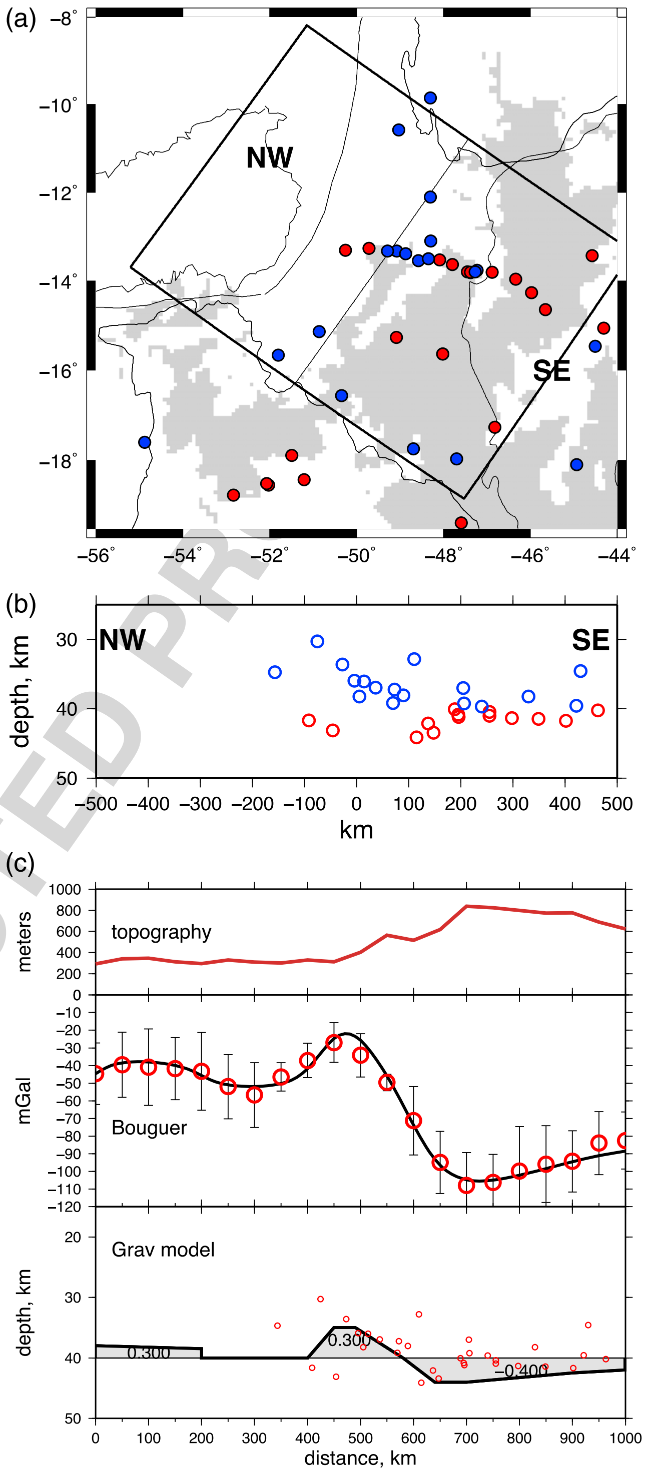

Figure 3. (a) Estimates of crustal thickness in Central Brazil [*Assumpção et al.*, 2012]. Blue and red circles denote thicknesses less or larger than 40 km, respectively. The rectangle indicates the area modeled with 2D structure. Shaded region shows elevations higher than 600 m. (b) Profile of Moho depths from the rectangular area projected along the NW-SE direction. (c) Forward modeling of Bouguer anomaly: (top) average topography, (middle) average Bouguer anomaly of 10 parallel NW-SE profiles, and (bottom) modeled bodies with numbers indicating density contrasts relative to the lower crust; red circles are Moho depths estimates from Figure 3b; thick line is the resulting Moho.

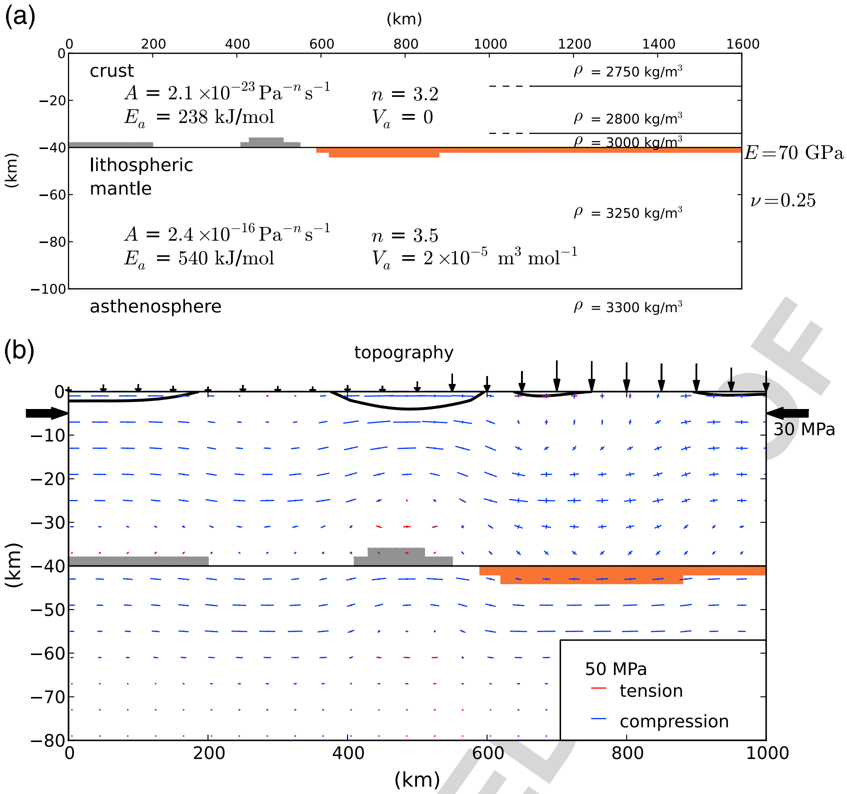

Figure 4. (a) Parameters of the numerical viscoelastic model. Gray areas show excess masses exerting a downward pull; brown areas are mass deficiencies with buoyant forces; topography was included but not seen in this scale. The rheological parameters are shown for the crust and lithospheric mantle. The density stratification of the crust and mantle is shown on the right. (b). Resulting non-lithostatic stress field after 100 Myr of simulation. Principal stresses are shown by blue bars (compression) and red bars (extension). Thin vertical arrows denote topography load. Thick horizontal arrows denote a regional compression of 30 MPa. Rupture limits for the Coulomb criteria with a friction coefficient of 0.5 are shown as solid curves; note the 200 km wide zone of high stresses in the upper crust above the area of thinned crust. Areas with low differential stresses on either side of the load are aseismic.

just above the load due to the high density, shallower mantle rocks in the area of thin crust. Compressional stresses in the upper crust are consistent with focal mechanism and hydraulic fracturing data (Figure 1).

[13] The narrow SW-NE-oriented Goiás-Tocantins seismic zone correlates better with the high gravity anomalies rather than surface geological features such as the TBL. Modeling of flexural deformation, due to load of high-density upper mantle along a belt of thin crust, shows that upper crust compressional stresses can reach ~100 MPa in a zone about 200 km wide, similar to the width of the seismic zone. Aseismic areas on each side of the GTSZ are due to extensional stresses in the peripheral bulge balancing a regional, plate-wide compressional stress. In addition, between 200 and 400 km east of the GTSZ, high topography and deep crust cause vertical compressional stresses balancing the horizontal regional compression, producing small deviatoric stresses, consistent with an aseismic zone. Farther than ~400 km from the axis of the GTSZ, seismicity starts to increase slightly again (Figures 1 and 2), possibly due to the vanishing of the extensional stresses in the peripheral bulge and predominance of the regional stresses again.

[14] Other seismic clusters occur in areas of high isostatic anomalies (Figure 2). The E-W trend of high gravity in the middle of the Amazon basin was modeled by *Zoback and Richardson* [1996] as a source of flexural stresses related to local seismicity. Other clusters are as follows: the N-S trending zone at the eastern margin of the Amazon craton (roughly along longitude 50°W), the Porto dos Gauchos seismic zone in the Parecis basin (~ 12°S, 57°W), and the area of the Pantanal basin continuing into the Chaco basin in Paraguay (from 16°S to 25°S, along the longitude 56–58°W). Large areas with isostatic anomalies lower than −20 or −30 mGal (such as in the Guaporé shield and the middle of the Parnaiba and Paraná basins) are almost completely aseismic (Figure 2).

[15] The Goiás-Tocantins seismic zone in Central Brazil is the best example of the importance of flexural deformation as a source of seismogenic stresses. Given that other clusters of seismicity also occur in areas with high isostatic anomalies, we conclude that flexural stresses are an important factor to explain mid-plate seismicity in most of mid-plate South American.

[16] **Acknowledgments.** We thank all colleagues from the universities of São Paulo and Brasília for collaboration over many years to produce the Brazilian seismic catalog. This work is supported by grants CNPq-30.9724/2009-0 and FAPESP-2011/10400-0.

References

Assumpção, M., and M. Araujo (1993), Effect of the Altiplano-Puna plateau, South America, on the regional intraplate stress, *Tectonophys.*, *221*, 475–496.

Assumpção, M., M. Feng, A. Tassara, and J. Julià (2012), Models of crustal thickness for South America from seismic refraction, receiver functions and surface wave tomography, *Tectonophys.*, http://dx.doi.org/10.1016/j.tecto.2012.11.014.

Barros, L. V., M. Assumpção, R. Quintero, and D. Caixeta (2009), The intraplate Porto dos Gaúchos seismic zone in the Amazon craton—Brazil, *Tectonophys.*, *469*, 37–47, doi:10.1016/j.tecto.2009.01.006.

Berrocal, J., Y. Marangoni, N. C. Sá, R. Fuck, J. E. P. Soares, E. Dantas, F. Perosia, and C. Fernandes (2004), Deep seismic refraction and gravity crustal model and tectonic deformation in Tocantins Province, Central Brazil, *Tectonophys.*, *388*, 187–199.

Calais, E., A. M. Freed, R. Van Arsdale, and S. Stein (2010), Triggering of New Madrid seismicity by late-Pleistocene erosion, *Nature*, *466*, 608–611.

Coblentz, D. D., and R. M. Richardson (1996), Analysis of the South American intraplate stress field, *J. Geophys. Res.*, *101*, 8643–8657.

Fairhead, J. D., and S. Maus (2003), CHAMP satellite and terrestrial magnetic data help define the tectonic model for South America and resolve the lingering problem of the pre-break-up fit of the South Atlantic Ocean, *The Leading Edge*, *22*, 779–783.

Grana, J. P., and R. M. Richardson (1996), Tectonic stress within the New Madrid seismic zone, *J. Geophys. Res.*, *101*, 5445–5458.

Johnston, A. C., and L. R. Kanter (1990), Earthquakes in stable continental crust, *Sci. Am.*, *262*, 68–75.

Karato, S.-I., and P. Wu (1993), Rheology of the upper mantle: A synthesis, *Science*, *260*, 771–778.

Lithgow-Bertelloni, C., and J. H. Guynn (2004), Origin of the lithospheric stress field, *J. Geophys. Res.*, *109*, B01408, doi:10.1029/2003JB002467.

Mooney, W. D., J. Ritsema, and Y. Hwang (2012), Crustal seismicity and maximum earthquake magnitudes (Mmax) in stable continental regions (SCRs): Correlation with the seismic velocity of the lithosphere, *Earth Planet. Sci. Lett.*, *in press*. Q2

Ranalli, G. (1987), Rheology of the Earth, 2nd ed., 413 pp., Chapman and Hall, London.

Sá, N. C. (2004), O campo de gravidade, o geóide e a estrutura crustal na América do Sul: Novas estratégias de representação. *Tese de Livre-Docência*, Universidade de São Paulo, 121 pp.

Soares, J. E., J. Berrocal, R. A. Fuck, W. D. Mooney, and D. B. R. Ventura (2006), Seismic characteristics of central Brazil crust and upper mantle: A deep seismic refraction study, *J. Geophys. Res.*, *111*, B12302, doi:10.1029/2005JB003769.

Stein, S., M. Liu, E. Calais, and L. Qingsong (2009), Mid-continent earthquakes as a complex system, *Seism. Res. Lett.*, *80*, 551–553.

Zoback, M. L., and R.M. Richardson (1996), Stress perturbation associated with the Amazonas and other ancient continental rifts, *J. Geophys. Res.*, *B101*(3), 5459–5475.

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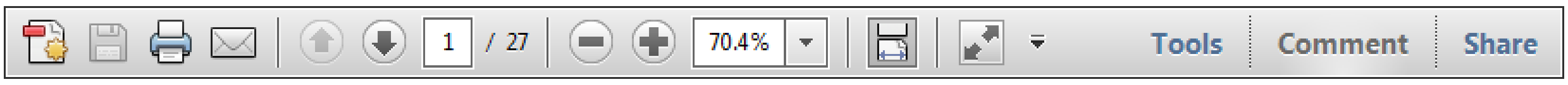

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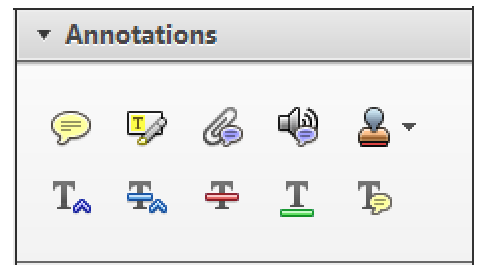

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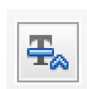

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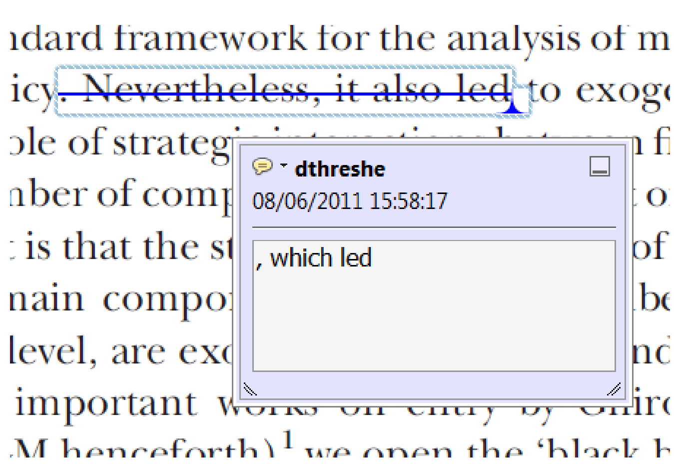

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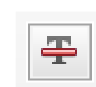

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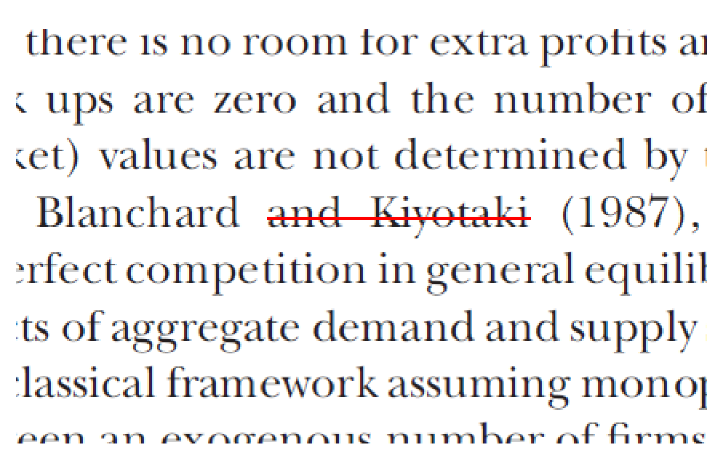

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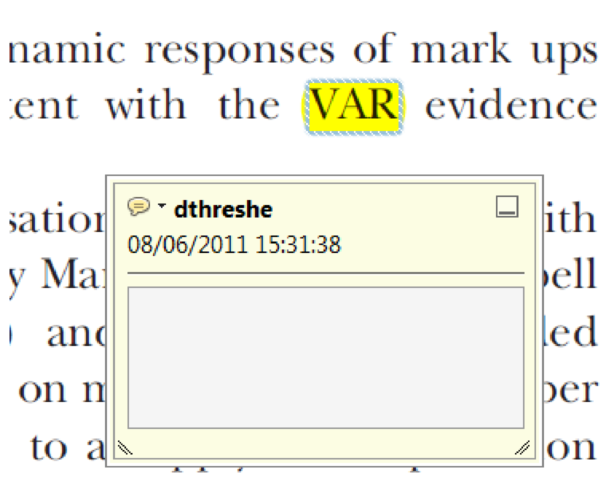

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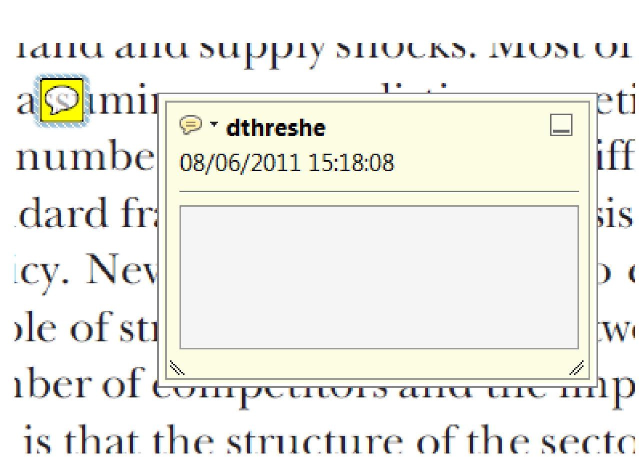

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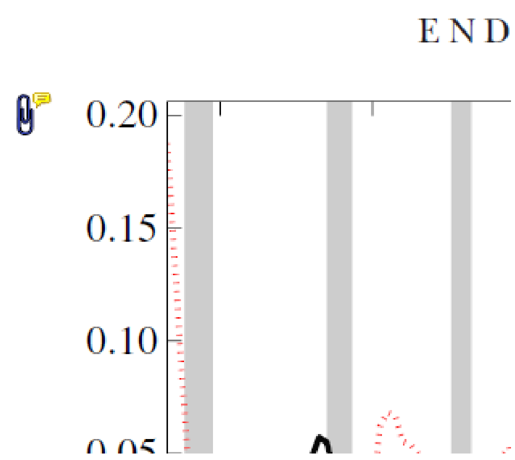

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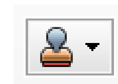

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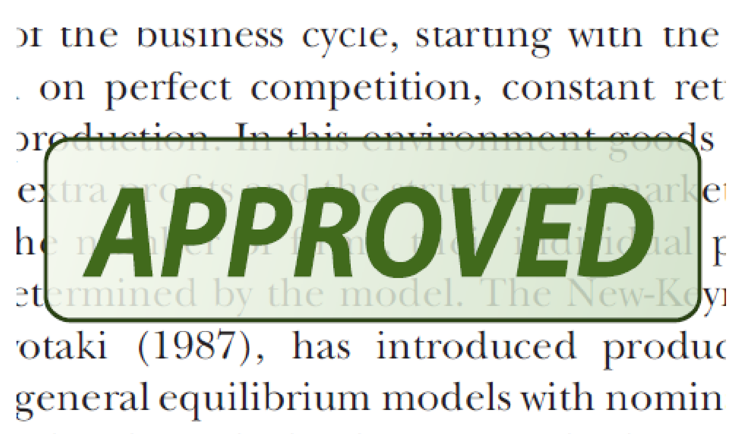

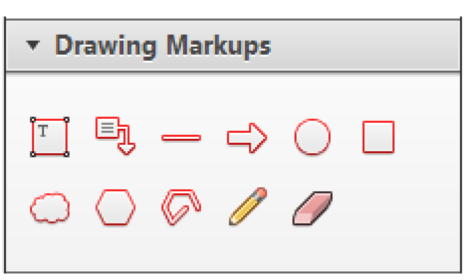

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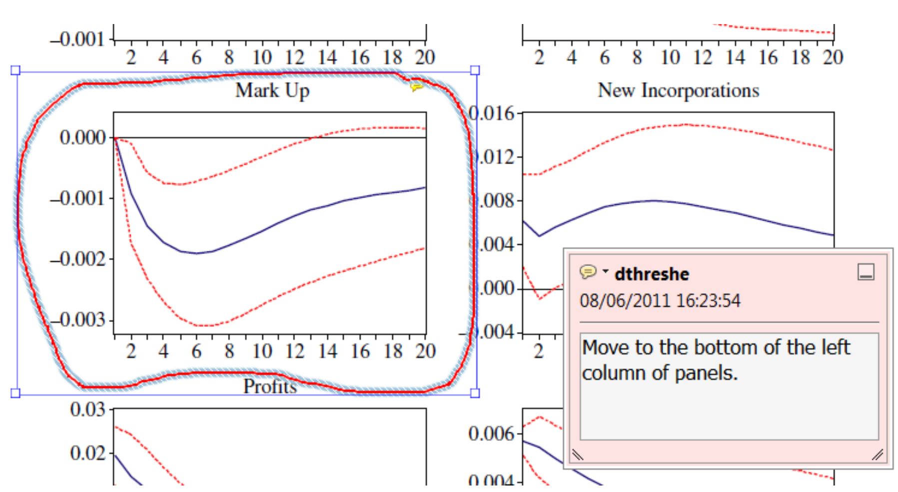

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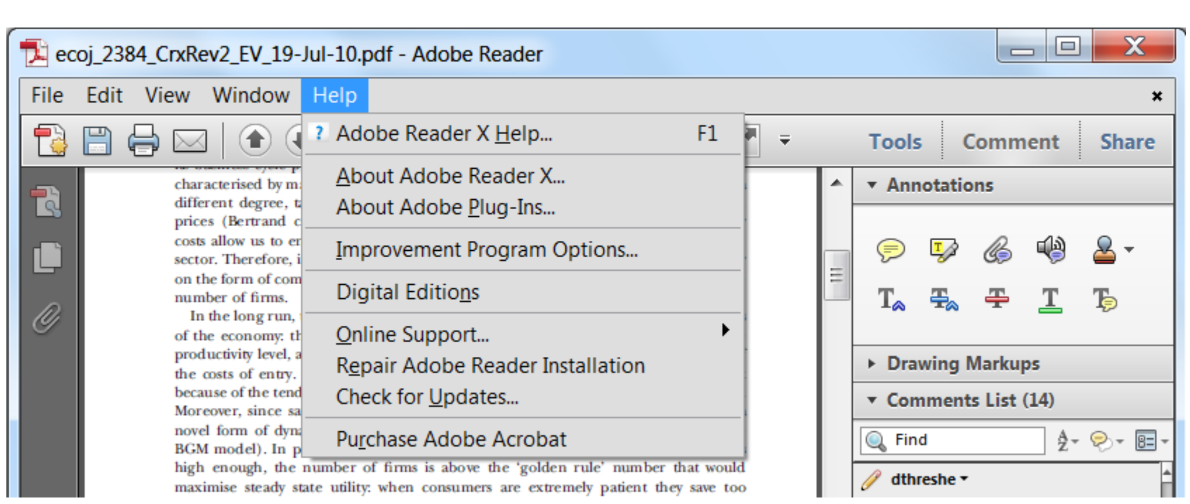

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