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STATE OF STATIC STRESS ON THE COSTA RICAN COCOS-CARIBBEAN PLATE INTERFACE: MECHANICAL INTERPRETATION FOR THE ORIGIN OF ASPERITIES ON THE SEISMOGENIC ZONE

ESTADO DE ESFUERZOS ESTÁTICOS EN LA INTERFACE DE PLACAS COCO-CARIBE EN COSTA RICA: INTERPRETACIÓN MECÁNICA PARA EL ORIGEN DE ASPEREZAS EN LA ZONA SISMOGÉNICA

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ABSTRACT: The forearc region along the Central American Subduction Zone shows a series of trench-parallel positive gravity anomalies with corresponding gravity lows along the trench and toward the coast. These features extend from Guatemala to northern Nicaragua. However, the Costa Rican section of the forearc does not follow this pattern due to the segmentation of the along-trench gravity low, the absence of the coastal low, and the presence of emerged continental mass along the forearc gravity high at the Nicoya Peninsula. Geodetic and seismological studies along the Costa Rican Subduction Zone suggest the presence of coupled areas in the seismogenic zone beneath the Nicoya Peninsula prior to the 7.6 Mw magnitude earthquake of September 5th, 2012. These areas have previously been associated with asperities. Based on the structure of the overriding plate, former publications have proposed a mechanical model for the origin of asperities along the Chilean convergent margin, in which the dense igneous material in the forearc of the overriding plate above the seismogenic zone modifies/disturbs the state of static stress and influences seismogenic processes. In Costa Rica, surface geology and gravity data indicate the existence of dense basalt/gabbro crust overlying the seismogenic zone where the coupling is present. Bouguer anomaly values in this region reach up to 120×10^{-5} m/s^2 and are the highest for Costa Rica. In this research, the state of static stress on the Cocos-Caribbean plate interface is calculated based on the geometry and on the density distribution of a 3D litosphere density model of the subduction zone as interpreted from gravity data from combined geopotential models. Results show a spatial correlation between the coupled areas at the Nicoya Peninsula and the presence of anomalies on the static state of stress on the plate interface. The stress anomalies were calculated for the normal component of the vertical stress on the seismogenic zone and were interpreted as being generated by the dense material which makes up the forearc in the area. The dense material

of the Nicoya Complex mafic rocks and the topographic load of the peninsula on the seismogenic zone lay a role in the distribution of coupled areas and the seismic behavior of the region, since the anomalies on the normal stress on the plate interface may increase the shear stress threshold to generate the rupture.
Keywords: Tectonic stress, asperities, seismogenesis, geophysics, gravimetry.

RESUMEN: La región del antearco a lo largo de la zona de subducción centroamericana muestra una serie de anomalías positivas de gravedad paralelas a la trinchera con anomalías negativas correspondientes, a lo largo de la fosa y hacia la costa. Estas anomalías se extienden desde Guatemala hasta el norte de Nicaragua. Sin embargo, el segmento costarricense del antearco no sigue este patrón debido a la segmentación de la anomalía negativa de la fosa, la ausencia de la anomalía negativa costera y la presencia de masa continental emergida en el lugar de la anomalía positiva del antearco en la Península de Nicoya. Estudios geodésicos y sismológicos a lo largo de la zona de subducción costarricense sugieren la presencia de áreas de acoplamiento en la zona sismogénica bajo la península de Nicoya previo al sismo de magnitud 7,6 Mw del 5 de setiembre de 2012. Estas áreas han sido asociadas anteriormente con asperezas. Publicaciones previas han propuesto un modelo mecánico para el origen de asperezas a lo largo del margen convergente chileno, basado en la estructura de la placa cabalgante. Basado en la estructura de la placa cabalgante, publicaciones previas han propuesto un modelo mecánico para el origen de asperezas a lo largo del margen convergente chileno, en el cual el material ígneo denso en el antearco de la placa cabalgante sobre la zona sismogénica, modifica el estado de esfuerzos estáticos en la interface de placas e influye en los procesos sismogénicos. En Costa Rica, la geología de superficie y los datos de gravedad indican la presencia de corteza densa compuesta por basaltos y gabros que sobreyace la zona sismogénica en donde el acoplamiento está presente. Los valores de anomalía de Bouguer en esta región alcanzan los 120×10^{-5} m/s^2 y son los más altos medidos para Costa Rica. En este trabajo, el estado de esfuerzos estáticos en la interface de placas Cocos-Caribe se calcula basado en la geometría y en la distribución de densidad de un modelo tridimensional de la litósfera de la zona de subducción interpretado a partir de datos de gravedad de modelos geopotenciales combinados. Los resultados muestran una correlación espacial entre las áreas acopladas en la Península de Nicoya y la presencia de anomalías en el estado de esfuerzos estáticos en la interface de placas. Las anomalías de esfuerzo se calcularon para la componente normal del esfuerzo vertical en la zona sismogénica y se interpretaron como originadas por el material denso que compone el antearco en el área. El material denso de las rocas máficas del Complejo de Nicoya y la carga topográfica de la península sobre la zona sismogénica influyen en la distribución de zonas acopladas y el comportamiento sísmico de la región. Esto se debe a que las anomalías en el esfuerzo normal a la interface de placas incrementan el umbral de esfuerzo cortante para generar la ruptura.
Palabras clave: Esfuerzos tectónicos, asperezas, sismogénesis, geofísica, gravimetría.

INTRODUCTION

The analysis of the state of stress on convergent margins has traditionally focused on the forces exerted by and on the subducted slab through ridge push occurring at the spreading centers and the slab pull, caused by the gravitational attraction of the dense slab (vanSummeren et al., 2014). Both the vertical and horizontal components of these forces have an influence on the dynamics of convergence. However, when considering the state of stress on the seismogenic segment of the plate interface, the influence of the overriding plate must also be taken into account. The geometry of the seismogenic zone and the distribution of mass on the plate above it, may control the rupture processes by directly influencing the mechanical conditions under which they take place.

The synoptic model of the Central American subduction zone by Lücke (2012) features the overall geometry of boundary surfaces and first order tectonic discontinuities of the convergent margin, such as the subducted slab of the Cocos plate. By considering the volume and density of materials in a three-dimensional space, this model contemplates the necessary parameters for the calculation of the state of stress on any modeled boundary surface. In this research, the tectonic processes that act on these surfaces are analyzed from the state of static stress point of view by means of calculation of the normal component of the vertical stress. The magnitude of this component of stress is product of the geometry of the boundary surface, the mass distribution of the lithosphere in terms of density contrasts, and the dynamic stress on a regional scale.

TECTONIC SETTING

The structure of the Costa Rican subduction zone is heavily influenced by the heterogeneity of the subducting Cocos plate. Upon its arrival at the Middle American Trench offshore Costa Rica, this plate is segmented in three morpho-tectonic domains defined by von Huene et al. (2000) as: a northwestern section with smooth bathymetric relief, a central seamount segment and a northeastern segment marked by the presence of the Cocos Ridge (Fig. 1).

In northwestern Costa Rica and southern Nicaragua, local earthquake seismic tomography data published by DeShon et al. (2006) and Syracuse et al. (2008), wide-angle refraction seismic by Sallarès et al. (2001) and a magnetotelluric survey by Worzewski et al. (2011) show a steeply dipping slab. For central Costa Rica, where the seamount segment of the Cocos plate subducts, local earthquake seismic tomography data by Husen et al. (2003), Arroyo et al. (2009) and Dinc et al. (2010) show a shallower subduction angle. The deep structure of the subduction zone for the Cocos Ridge segment is less constrained with receiver function data by Dzierma et al. (2011) and earthquake hypocenter data by Arroyo (2001) and Arroyo et al. (2003), showing the presence of a steeply subducting slab down to a depth of 70 km.

The geometry of the subduction zone was studied by Lücke (2012) by means of a synoptic model which takes into account three-dimensional data (local earthquake seismic tomographies), two-dimensional cross sections (refraction and reflection seismic, magnetotellurics) and one-dimensional data (receiver functions, earthquake hypocenters) to constrain a three-dimensional density model from gravity data interpretation. A cross-section of the model is shown in figure 2A.

The state of static stress on the plate interface is primarily influenced by the distribution of the masses above it. For this reason, when calculating static stress, the geology of the overriding plate has been taken into account in the density model. The Costa Rican forearc is characterized by the presence of mafic igneous complexes above the seismogenic zone. The northwestern region of the Costa Rican forearc shows the presence of ultramafic rocks cropping out along the Santa Elena Peninsula (Gazel et al., 2006), and most significant in volume, the presence of basalts and gabbros of the Nicoya Complex (Denyer et al., 2014) (Fig. 2B). In the Central Pacific region of the forearc, basalts from the Tulín Formation (Arias, 2000) crop out along the Herradura Promontory. In the southern end of the forearc, basalts and gabbros from the Osa Igneous Complex (Buchs et al., 2009) crop out along the Osa Peninsula.

These mafic rocks have a higher density than their environment and this contrast is reflected in the presence of positive Bouguer anomalies (disturbances) along the forearc. The most significant anomaly occurs along the Nicoya Peninsula, where Bouguer anomaly values reach up to 120×10^{-5} m/s^2. Figure 2C shows the Bouguer anomaly (disturbance) map for northwestern Costa Rica, calculated from gravity data of the combined geopotential model EGM2008 (Pavlis et al., 2012). The interpretation of these anomalies and the effects of the dense material on the seismogenic zone is the focus of this study.

PREVIOUS WORK

In the context of a subduction zone, the subject of stress is closely linked with the presence and characterization of asperities. From a geological point of view, the concept of an asperity has been associated with the relief of oceanic plate in terms of bathymetric features that have entered the subduction system (Barckhausen et al., 1998) and thus, have a direct influence in the interaction with the overriding plate (Scholz & Small, 1997). However, in this paper, an asperity

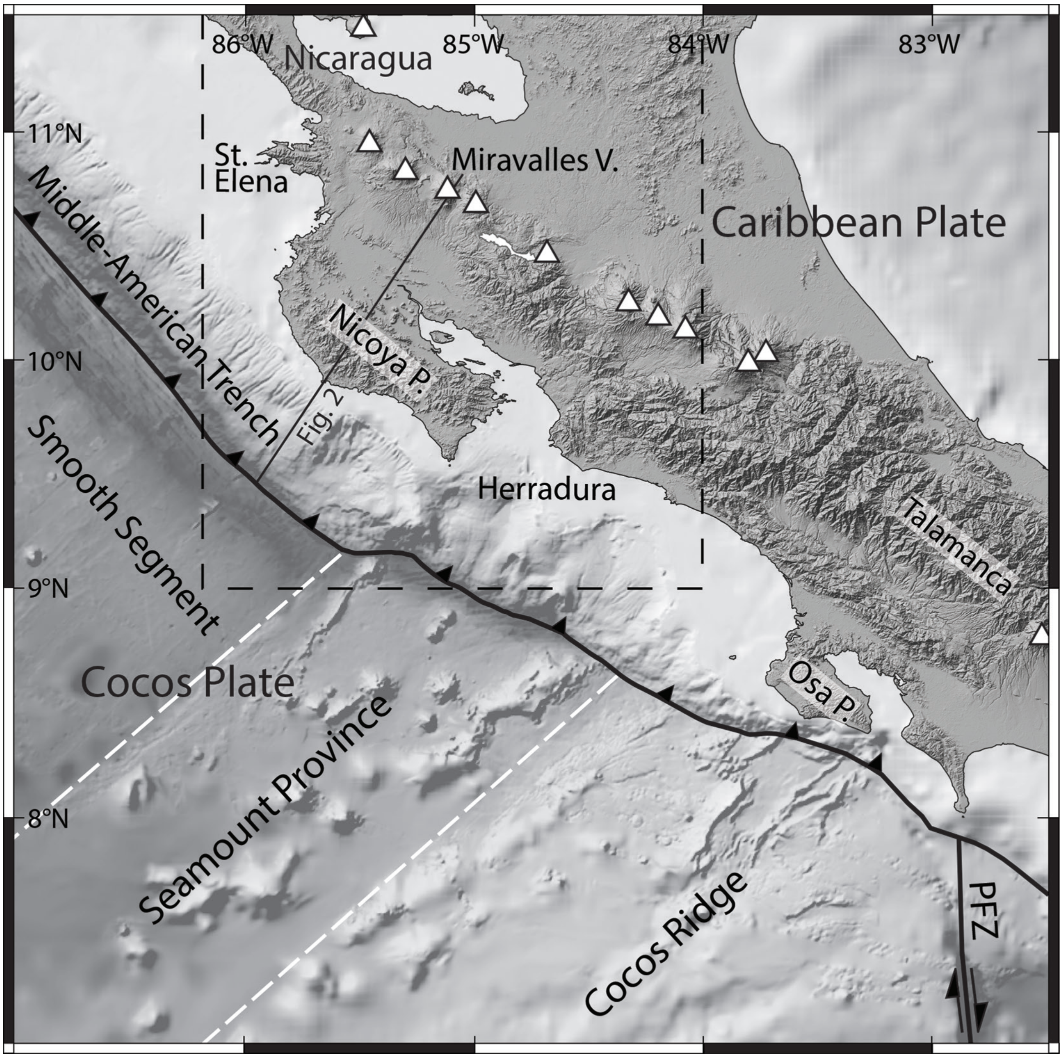

Fig. 1: Tectonic setting of the Costa Rican subduction zone. Black stippled box shows the study area. Thin black line shows the location of the cross-section shown in figure 2A. Black dented line shows the axis of the Middle American Trench. White filled triangles show the main Quaternary volcanoes. PFZ: Panama Fracture Zone.

is defined from the point of view of the behavior of the seismogenic zone and its response to plate convergence as defined by Lay & Kanamori (1981), who describe asperities as zones of high shear strength on the rupture plane and large coseismic slip due to the buildup of stress prior to a rupture. In the seismological context, asperities are linked to coupled zones in which ruptures and slips are episodic instead of occurring gradually over time.

This asperity model has been proposed for areas in which geodetic measurements indicate a large coseismic slip and are characterized by low seismicity with long interseismic periods. Such is the case of the Nicoya Peninsula in Costa Rica, where Feng et al. (2012) propose the existence of a coupled zone prior to the 7.6 Mw earthquake that occurred on September 6th, 2012.

Regarding the cause of asperities, several factors have been studied to explain the reason why these zones show a stick-slip behavior. Other than considering the effects of paleo-bathymetric features that have been incorporated into the subduction zone

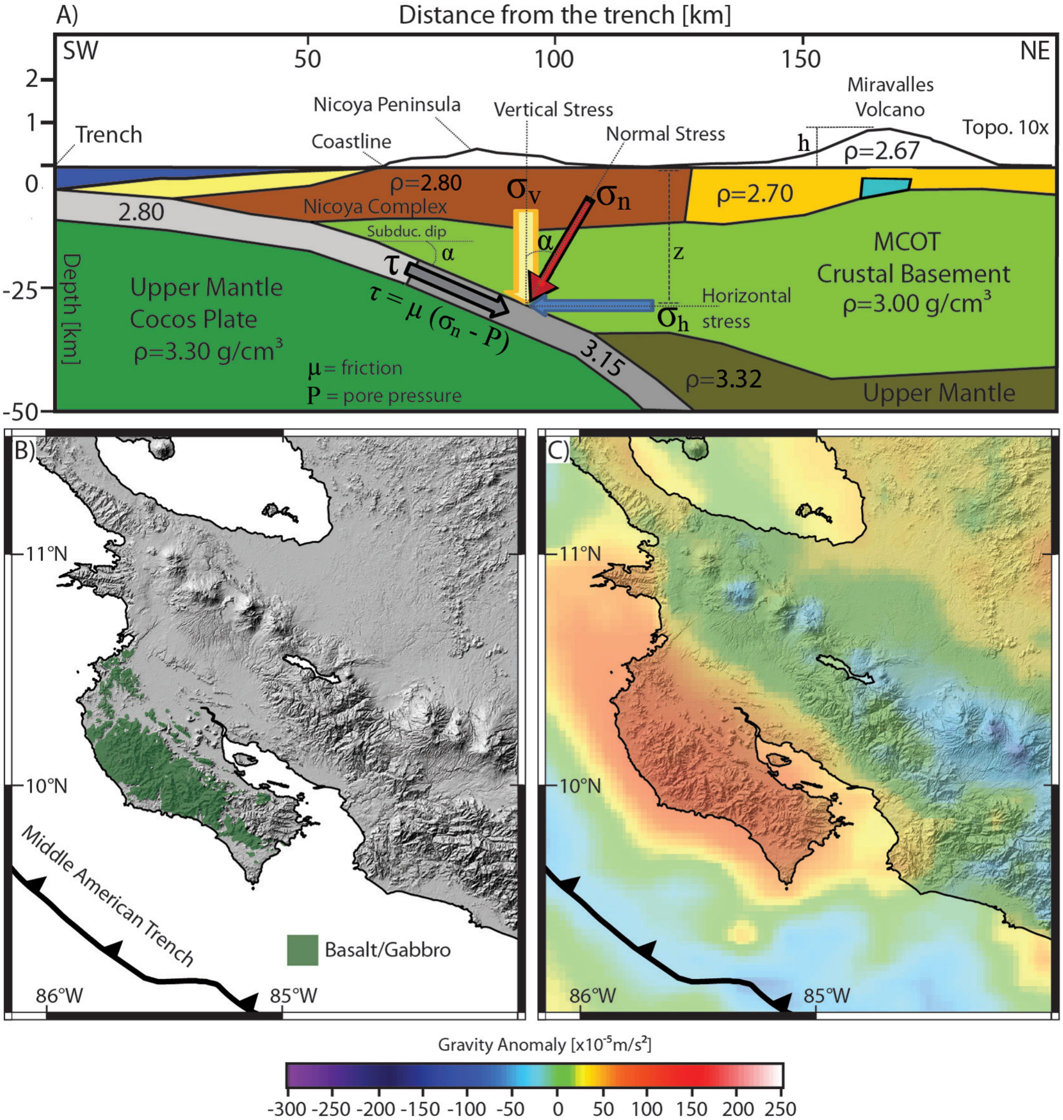

Fig. 2: A) Density model (Lücke, 2012) and distribution of static stress for a given point on the plate interface based on Tassara (2010). B) Surface distribution of basalt/gabbro units belonging to the Nicoya Complex (Denyer & Alvarado, 2007). C) Gravity anomaly (disturbance) map (Bouguer onshore, free-air offshore) from EGM2008 combined geopotential model (Pavlis et al., 2012).

(Scholz & Small, 1997), another factor that may influence this behavior is the composition of clay minerals that make up the shear surface on the subduction channel. One example of this is the mineralogical change from smectite to illite. For instance, Vrolijk (1990) studied the influence of the smectite metamorphosis on the strengthening of materials and its relation to the onset of seismicity.

Various authors have also studied the relationship between the presence of asperities on the seismogenic zone and the features observed on the gravity field. Song & Simons (2003) correlate negative gravity anomalies over the seismogenic zone with areas of high coseismic slip, and thus assume that these negative anomalies correlate with asperities. However, Tassara (2010) and

Sobiesiak et al. (2007) observe a correlation of coupled zones with positive gravity and isostatic residual anomalies. According to Tassara (2010), this contradiction is due to the erroneous interpretation by Song & Simons (2003) that an asperity is present in the area of greatest seismic moment release during an earthquake, and that the gravity lows are caused by depressed bathymetry due to seismic coupling of the forearc. Tassara (2010) and Sobiesiak et al. (2007) propose that, for the Chilean convergent margin, the asperities correlate with gravity highs that are caused by the presence of dense material in the forearc above the seismogenic zone. This dense material, according to Tassara (2010), increases the shear stress threshold for rupture by generating an anomalously high normal stress on the frictional plane of the subduction zone.

This research focuses on the influence of the static stress state on the behavior of the subduction zone in northwestern Costa Rica in order to explain the origin of the coupling of the seismogenic zone from a mechanical point of view.

METHODS

Modeling of the Structure of the Forearc and Subduction Zone

The calculation of the static stress derives from the modeled density structure of the lithosphere, interpreted from gravity data. The model of the three-dimensional density structure was achieved through forward modeling using the software IGMAS+ (Schmidt et al., 2010). This software is based on the approximation of three-dimensional bodies by means of polyhedra, according to Götze (1976) and Götze & Lahmeyer (1988). The modeling is carried out interactively by creating cross-sections from which the polyhedra are calculated from the input of vertices. The densities are homogeneous for each polyhedron and can be directly assigned or calculated from inversion of the gravity data. In order to constrain the geometry and density values of the model, and to restrict the non-uniqueness, other geophysical data are included. A further description of the density model, geometry of boundary surfaces, and geophysical constraints can be found in Lücke (2012), Lücke (2014), Köther et al. (2012), and Lücke et al. (2010).

Calculation of Static Stress

The static stress field was calculated by means of a plug-in within the IGMAS+ software. The calculation directly considers the geometry of the modeled surfaces, the magnitude of the densities and the volume of the polyhedra. The vertical stress (σ_v) is the magnitude of the lithostatic pressure (equation 1) exerted on a point at a depth of “z” by the material on top of it with a density of “ρ” and the acceleration of gravity (γ). The value for the normal gravity “γ” was calculated with the international gravity formula WGS1984 (National Imagery and Mapping Agency, 1997) and has a magnitude of $\gamma = 978188.38$ m/s^2 for a latitude of 10°N, which represents central Costa Rica. Equation 1 describes the calculation of vertical stress at a given depth for a single rock layer with a homogeneous density.

Equation (1): $\sigma_v = \rho \cdot \gamma \cdot z$

The combined effect of the lithostatic pressure (σ_v) exerted by several layers at a depth of “z” below the geoid, taking into account the topographic load caused by masses that reach a height of “h” above the geoid is described in equation 2, after Gutknecht et al. (2014):

Equation (2): $\sigma_v = \int_h^z \gamma\rho(z)dz$

The normal stress on a given dipping surface is known by the sum of the vertical (σ_v) and horizontal (σ_h) stress components that are perpendicular to the surface. In the context of convergent plate margins, Tassara (2010) defines the normal stress (σ_n) in terms of the orientation of components for a given point on the plate interface of the subduction zone. This definition is depicted in figure 2A and represented in equation 3, where α is the subduction dip and σ_h is the horizontal stress caused by plate convergence.

Equation (3): $\sigma_n = (\sigma_v \cos\alpha + \sigma_h \sin\alpha)$

The normal component of vertical stress (σ_{vn}) encompasses the effect of the forearc density structure and the geometry of the plate interface. Equation 4 from Gutknecht et al. (2014), shows how this component is calculated for a model with "n" amount of layers and accounting for the effect of topography. The geometry of the plate interface is reflected in the dip angle (α) of the subduction zone.

Equation (4): $\sigma_{vn} = \gamma \cdot \cos^2\alpha \cdot (\rho_{topo} \cdot h_{top}o + (\rho_1 \cdot h_1 + \rho_2 \cdot h_2 + \ldots + \rho_n \cdot h_n))$

The calculation of stress anomalies ($\Delta\sigma_{vn}$) for this study (equation 5) is carried out by subtracting the stress generated by a reference body of constant density from the absolute values of the normal component of vertical stress. The value of the reference density (ρ_r) is defined in order to eliminate the global effect of the depth gradient, which tends to mask the lateral heterogeneities of the stress field. In contrast with Gutknecht et al. (2014), a single reference density was used, since in this research, the focus of the calculation of stress anomalies is on the effects of these anomalies on the seismogenic zone. Thus, a density of 3.32 g/cm^3 was chosen as reference since it was determined that it optimally removed the effect of the depth gradient for the shallower 50 km of the subduction zone.

Equation (5): $\Delta\sigma_{vn} = \gamma \cdot \cos^2\alpha \cdot (\rho_{topo} \cdot h_{topo} + (\rho_1 \cdot h_1 + \rho_2 \cdot h_2 + \ldots + \rho_n \cdot h_n) - (\rho_r \cdot h_r))$

Influence of Normal Stress on Seismogenic Processes

According to Scholz, (1998), tectonic earthquakes rarely occur by the generation of a new fracture. Instead, they happen when there is slip along the surface of a preexisting plane of discontinuity. Therefore, tectonic seismicity is a frictional process and not an active fracturing one. Hence, the importance of studying the mechanical elements that control slip along the plate interface. For the purpose of this study, when referring to the word "rupture", it should be understood as the beginning of slip along an existing plane of discontinuity and not as the appearance of a new one.

It is using Coulomb's law of friction, that Tassara (2010) defines "τ" as the shear stress on the plate interface (equation 6), which, assuming that there is no cohesion, is dependent on: the static friction coefficient "μ" (Cattin et al., 1997), the pore pressure of fluids in the material (P), and more relevant for this interpretation, the normal stress (σ_n).

Equation (6): $\tau = \mu\ (\sigma_n - P)$

According to Lowry (2006), the slip along a fault plane occurs when the shear stress (τ) overcomes the friction given by $\mu \cdot \sigma_e$, where σ_e is the effective normal stress as defined in equation 7. Thus, the normal stress, among other factors such as the static friction coefficient and pore pressure, determines the shear stress that must be exerted on the plate interface in order to generate slip and cause an earthquake on the seismogenic zone.

Equation (7): $\sigma_e = \sigma_n - P$

STATIC STRESS ON THE COCOS-CARIBBEAN PLATE INTERFACE

Absolute Normal Component of the Vertical Stress

The static stress field on the interplate surface was calculated by considering the geometry of the subducted slab and the lithospheric density distribution from the 3D model by Lücke (2012). This calculation takes into account the influence of masses above the geoid by adding the isostatic load generated by the topography with an assigned density of 2.67 g/cm^3. The magnitude of the absolute stress (Fig. 3A) is dominated by the increment in lithostatic pressure due to an increment in depth. This magnitude provides quantitative information in absolute terms about the pressure conditions on the plate interface.

The results show absolute values of the normal component of vertical stress reaching a maximum of 4000 MPa at a depth of 200 km. Due to

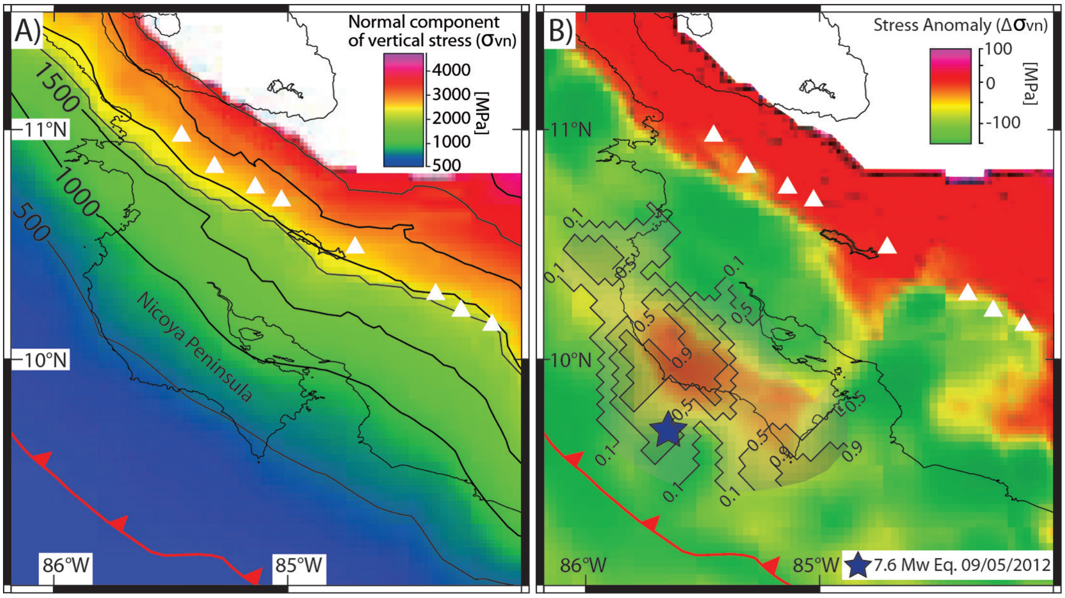

Fig. 3: A) Magnitude of the normal component of the vertical stress (σ_{vn}) calculated on the top of the subducted Cocos slab. Contours each 500 MPa. Grey lines depict the coastline. B) Anomalies of the normal component of vertical stress ($\Delta\sigma_{vn}$) on the top of the subducted Cocos slab calculated on a 5x5 km grid, relative to a reference density of 3.32 g/cm^3 with a density of 2.67 g/cm^3 for the topographic mass. Contours show the degree of coupling on the seismogenic zone modeled by Feng et al. (2012).

the controlling effect of depth on the magnitude of the vertical stress, the absolute values reflect the geometry of the subducted slab. The contrasts in the stress field produced by local heterogeneities caused by a contrast in density of the forearc rocks, are masked by the strong vertical gradient of the lithostatic pressure.

Normal Stress Anomalies

Although the magnitude of absolute stress may provide an important parameter for applications such as petrological modeling, the strong correlation with depth makes it difficult to interpret the effect that forearc heterogeneities may have on the seismogenic zone. For this reason, it is necessary to dismiss the large-scale effect of depth on the stress field. This is achieved by considering the normal stress field generated by a reference body of constant density, and by subtracting it from the stress calculated for the density model (equation 5). This allows to highlight the lower scale differences in the stress field caused by local and lateral heterogeneities, in this case, on the seismogenic zone.

Figure 3B shows the results of the calculation of anomalies of the normal component of vertical stress on the Cocos-Caribbean plate interface. The anomalies were obtained by subtracting the stress field generated by a reference body with a constant density of 3.32 g/cm^3.

The results show an elongated, NW-SE trending positive stress anomaly along the western part of the Nicoya Peninsula. The location of this anomaly correlates with the zones of highest seismic coupling of the seismogenic zone modeled by Feng et al. (2012).

Considering the density of the reference body (3.32 g/cm^3), the change from positive to negative values in the magnitude of the stress anomalies, indicates the level at which the negative normal stress anomalies from the crustal material reach an equilibrium with the higher stress created by the asthenospheric material. This state is reached when the effect of the lower crustal densities is compensated by the higher densities of the lower mantle, which consequently, should occur at a depth located below the lithosphere-asthenosphere boundary. However, the effect of the topographic load may be large enough to offset this equilibrium. This is the case for the area beneath the Talamanca region of Costa Rica, where the stress anomalies relative to a reference body with a density of 3.32 g/cm^3 become positive approximately at the depth contour of 60 km for the slab, between 10 and 15 km shallower than the lithosphere-asthenosphere boundary. This is observed in areas where the Moho is constrained by receiver functions (Dzierma et al., 2010) and outlined by gravity modeling (Lücke, 2014), thus providing information on the crustal thickness.

MECHANICAL MODEL FOR THE ORIGIN OF ASPERITIES

Considering the frictional nature of tectonic seismicity described by Scholz (1998), it is necessary for the shear stress to surpass the friction on the preexisting plane in order to generate rupture. The friction is controlled in part by the effective normal stress. The shear stress on the rupture plane increases with time due to convergence and the process of subduction. As an initial model, the shear stress increases during the interseismic period without surpassing the threshold for rupture. If at this stage an entirely elastic behavior of the subduction system is assumed, this increase in stress without displacement along the plane results in deformation of the overriding plate, which can be measured by surface observations. The model of the coupling of the seismogenic zone described by Feng et al. (2012) assumes an elastic behavior of the forearc and considers that the deformation observed at the surface reflects the state of coupling of the seismogenic zone, thus providing a way of identifying asperities. However, the behavior of the lithosphere is not entirely elastic. Part of the deformation may be assumed by fragile deformation due to displacement along faults at a shallow level of the forearc and ductile behavior of materials at greater depths. Although a purely elastic behavior of the forearc may be an unrealistic scenario, it is clear that the seismogenic zone along the Nicoya Peninsula shows an episodic occurrence of earthquakes with significant seismic moment release, separated by long interseismic periods. This behavior of the seismogenic zone and the models from geodetic observations are consistent with the presence of asperities.

The anomalously high normal stress on the plate interface leading to an increment in friction --which requires a higher shear stress along the preexisting rupture plane for slip to occur-- is interpreted from the correlation of the coupled zones location and the stress anomalies on the seismogenic zone. This interpretation of the forearc structure control on the behavior of the seismogenic zone has been proposed by Tassara (2010) for the Chilean subduction zone. Although asperities may be caused by multiple factors, the lateral heterogeneity in the density structure of the forearc has a direct influence on the state of stress on the plate interface, thus influencing the seismic behavior of the seismogenic zone as described by Sobiesiak et al. (2007) and Tassara (2010).

In the case of the Chilean forearc, studied by the abovementioned authors, the stress anomalies are caused by dense material from mafic intrusive rocks originated from magmatic processes related to the Jurassic volcanic arc. The stress anomalies observed along the Nicoya Peninsula are caused by basalts and gabbro belonging to the Nicoya Complex, an accreted terrain of ancient oceanic crust. The presence of these dense rocks on top of the seismogenic zone is corroborated by surface geology (Denyer et al., 2014) and result in Bouguer anomalies highs reaching 120×10^{-5} m/s^2 in this area. The density distribution of the forearc on the location of this gravity anomaly modeled in three dimensions by Lücke (2012) is the input for the stress calculations in this research.

Part of the anomalous stress condition is also caused by the topographic load on top of the seismogenic zone. The lithostatic load generated by the positive topography of the peninsula is absent in the surroundings of the main anomaly, which, on the contrary, have a negative relief. This condition of positive relief on top of the seismogenic zone is repeated in the Osa Peninsula. Wang & He (1999) state that for a low dipping, hypothetical frictionless fault (μ=0), the topographic load actually causes tension due to deviatoric horizontal stress. However, in presence of an effective coefficient of friction ($\mu' > 0$), the increase in total topographic relief will result in an increase in the margin-normal compression. The latter would be the case for the seismogenic zone in Nicoya, where the presence of shear force along the subduction fault --acting against the effect of the shear stress-- must be assumed in order to have a coupled state during the interseismic period.

The combined effect of the pressure caused by the higher density of the forearc rocks and the topographic load is reflected in the stress anomalies shown in figure 3B. These stress anomalies on the plate interface could be a contributing factor to the coupling observed by Feng et al. (2012), and may be one of the causes of the existence of asperities on the seismogenic zone beneath the Nicoya Peninsula. This interpretation follows the hypothesis of Tassara, (2010) where vertical stress anomalies caused by dense material in the forearc correlate with zones of high seismic moment release.

In relation to the distribution of the stress anomalies and coupling of the seismogenic zone, the epicenter of the 7.6 Mw September 5th 2012 earthquake is located on the trench ward edge of the anomaly and the coupled zone. The location of this event is consistent with observations that indicate that rupture nucleates at the edge of the asperities.

In terms of rupture and slip propagation, Song & Simons (2003) consider that ruptures propagate toward zones of lower coupling, which, due to their lower shear strength, can assume a greater amount of displacement. However, Tassara (2010) considers that once the rupture process is initiated, the decrease in the friction coefficient along the slip plane caused by the transition from a static to a dynamic state ($\mu_{dynamic} < \mu_{static}$), causes the zone with the highest coupling of the asperity to slip. This is due to the disturbance of the state of equilibrium prior to the initial rupture, which implies that the zone of the asperity with the highest coupling was subjected to a higher shear stress and should release the highest seismic moment. The higher shear strength on the slip plane due to shear stress over a frictionally coupled area of a fault is explained by Wang & He (1999) who state that the shear force increases quadratically with the width of the coupled zone.

CONCLUSIONS

The stress field calculations based on the regional density model allow the quantification of parameters of lithostatic pressure and static stress components acting on modeled surfaces or fixed depths. These parameters can be used as constraints for the modeling of tectonic, magmatic, and metamorphic processes. In terms of the study of the subduction zone, constraining the pressure and stress conditions is key to understanding mineralogical changes caused by dehydration reactions (*sensu* Hacker et al., 2003; Ranero et al., 2005) which have a direct influence on the behavior of intermediate depth seismicity. These interpretations require absolute magnitudes for pressure, a parameter which can be determined by the absolute stress calculated in this work.

The stress anomalies, obtained by subtracting the influence of the lithostatic gradient, provide insights on the presence and contributing cause of asperities on the seismogenic zone. The positive anomalies of the normal component of vertical stress on the Nicoya seismogenic zone correlate with the areas of high coupling coefficient modeled by Feng et al. (2012) from geodetic observations, which are considered asperities in the sense of Lay & Kanamori (1981). The origin of the asperities may be interpreted by a mechanical model in which the higher normal stress on the slip plane of the seismogenic zone leads to a higher shear strength along the plane as proposed by (Tassara, 2010). This model in which the density structure of the forearc controls the behavior of the seismogenic zone is valid for the northwestern Costa Rican subduction zone.

The correlation of the presence of asperities of the seismogenic zone in areas of positive gravity anomalies proposed by Sobiesiak et al. (2007) for the Chilean forearc is also found in the Costa Rican margin. This contrasts with the hypothesis by Song & Simons (2003) who interpreted a correlation between negative gravity anomalies and seismic asperities.

The surface geology and the three dimensional density modeling demonstrate that the cause of the anomalous stress on the seismogenic zone is the presence of dense mafic rocks from the Nicoya Complex. In addition to the presence of this rock unit with higher density than the surrounding rocks, the topographic load of the positive relief of the Nicoya Peninsula, located on top of the seismogenic zone, contributes to the increase in vertical stress due to the lithostatic load and the frictional state of the plate interface. The correlation between coupled zones on the seismogenic zone and geological bodies of high density (characterized by positive gravity anomalies and cause positive stress anomalies) is consistent with results by Sobiesiak et al. (2007), Tassara (2010) and Gutknecht et al. (2014) for the Chilean convergent margin.

The analysis of the state of static stress on the seismogenic zone of the Nicoya Peninsula allows for an interpretation of how the density structure of the forearc may influence the behavior of seismogenic processes. In this case, the possibility of determining the forearc density structure over the seismogenic zone by means of detailed direct observation of surface geology might shed light on origin of the anomalies. It may be possible to apply this model to the study of submerged areas of the forearc along the Central American subduction zone which show a similar gravimetric response and may represent asperities but are not accessible for geodetic observations.

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