MARINE GEOPHYSICS

New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure

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Gravity models are powerful tools for mapping tectonic structures, especially in the deep ocean basins where the topography remains unmapped by ships or is buried by thick sediment. We combined new radar altimeter measurements from satellites CryoSat-2 and Jason-1 with existing data to construct a global marine gravity model that is two times more accurate than previous models. We found an extinct spreading ridge in the Gulf of Mexico, a major propagating rift in the South Atlantic Ocean, abyssal hill fabric on slow-spreading ridges, and thousands of previously uncharted seamounts. These discoveries allow us to understand regional tectonic processes and highlight the importance of satellite-derived gravity models as one of the primary tools for the investigation of remote ocean basins.

Fracture zones (FZs) spanning the ocean basins reveal the breakup of the continents and the geometry of sea-floor spreading (*1*). The exact intersection points of the FZs along conjugate continental margins are used for precise reconstruction of the continents (*2*–*4*). These FZ intersections are commonly buried by several kilometers of sediments that flow off the continents to fill the voids created by the thermal subsidence of the rifted margins (*5*). This sediment cover extends hundreds to thousands of kilometers out onto the oceanic lithosphere, resulting in a relatively flat and featureless sea floor. Reflection seismic profiles can reveal the underlying basement topography of the FZs, but the data coverage is usually insufficient to map out the intersections. In areas of thin sediment cover, the topographic ridges and troughs along the FZs produce large gravity anomalies that are easily traced across the ocean basins (Fig. 1). However, when the topography becomes buried by sediment, the original density contrast of the sea-floor topography is reduced, resulting in more-subdued, and sometimes sign-reversed, gravity signatures (*6*). Moreover, as the lithosphere ages and cools, the sea floor subsides, causing a blurring of the gravity anomalies; smaller wavelengths of the gravity field become less well-resolved with increasing water depth. Previous global marine gravity models derived from satellite altimetry had sufficient accuracy and coverage to map all FZs in unsedimented sea floor (*7*), but the 3 to 5 mGal of gravity noise blurred the small signatures of sediment-covered topography such as seamounts and FZs. Here we report on a new global marine gravity model having ~2-mGal accuracy that is providing a dramatically improved resolution of the 80% of the sea floor that remains uncharted or is buried beneath thick sediment.

Gravity-field accuracy derived from satellite altimetry depends on three factors: altimeter range precision, spatial track density, and diverse track orientation. Two altimeter data sets with high track density have recently become available (CryoSat-2 and Jason-1) to augment the older altimeter data (Geosat and ERS-1), resulting in improvement by a factor 2 to 4 in the global marine gravity field. Their newer radar technology results in a 1.25-times improvement in range precision that maps directly into gravity-field improvement (*8*). The new altimeters also contribute more than 70 months of data, as compared with the 31 months provided by the older satellites. CryoSat-2 has provided the most dense track coverage, because although it has a nominal 369-day repeat orbit period, the ground tracks are allowed to drift within a 5-km band, so after 4 years in orbit it has provided a nominal track spacing of about 2.5 km. Jason-1 provided 14 months of dense track coverage during its geodetic phase, resulting in a track spacing of 7.5 km.

Most of the improvement in the altimeter-derived gravity field occurs in the 12- to 40-km wavelength band, which is of interest for the investigation of structures as small as 6 km. The current version of the altimeter-derived gravity field has an accuracy of about 2 mGal (*8*). Unlike terrestrial gravity, where coverage is uneven, these accuracies are available over all marine areas and large inland bodies of water, so this gravity provides an important tool for exploring the deep ocean basins. At scales smaller than 200 km, variations in marine gravity primarily reflect

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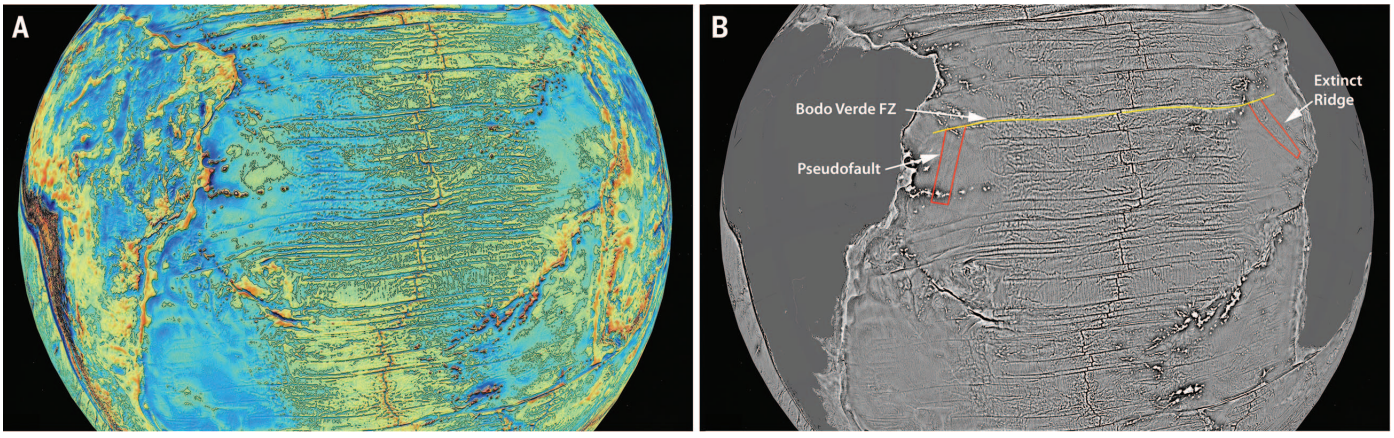

Fig. 1. Ocean gravity maps. (**A**) New marine gravity anomaly map derived from satellite altimetry reveals tectonic structures of the ocean basins in unprecedented detail, especially in areas covered by thick sediments. Land areas show gravity anomalies from Earth Gravitational Model 2008 (*15*). (**B**) VGG map derived from satellite altimetry highlights FZs crossing the South Atlantic Ocean basin (yellow line). Areas outlined in red are small-amplitude anomalies in areas where thick sediment has diminished the gravity signal of the basement topography. The full-resolution gravity anomaly and VGG models can be viewed in Google Earth using the following files: ftp://topex.ucsd.edu/pub/global_grav_1min/global_grav.kmz and ftp://topex.ucsd.edu/pub/global_grav_1min/global_grav_gradient.kmz. The grids are available in the supplementary material, as well as at the following FTP site: ftp://topex.ucsd.edu/pub/global_grav_1min.

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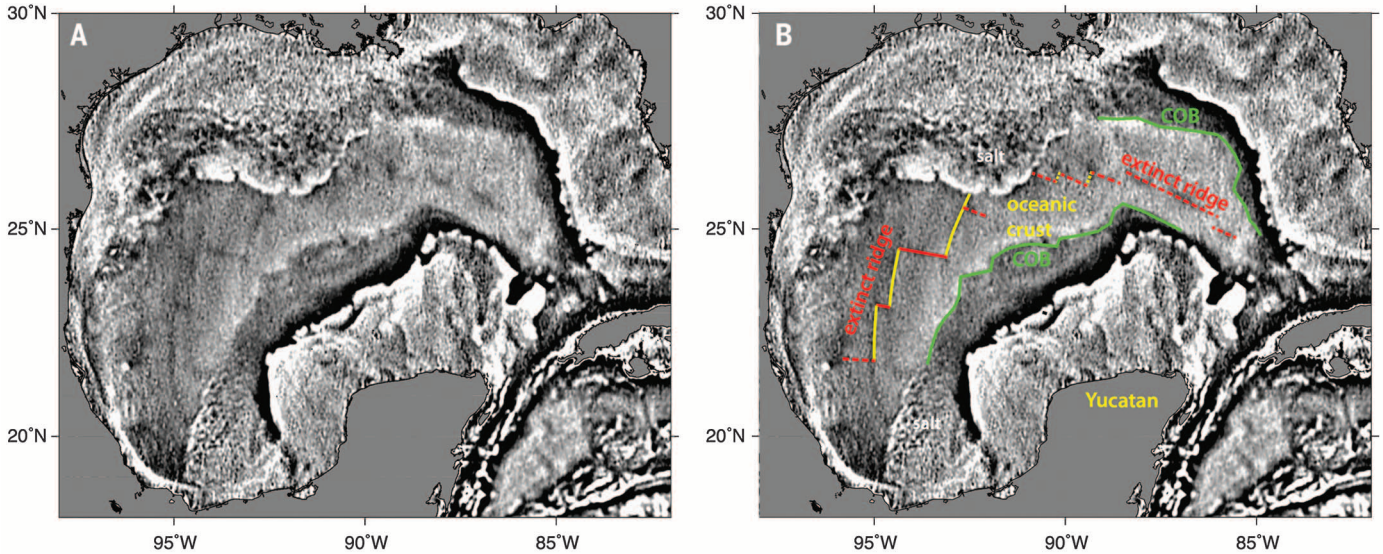

Fig. 2. Gulf of Mexico VGG. (**A**) Uninterpreted. (**B**) Our interpretation of tectonic structures, after Pindell and Kennan (*9*). The VGG reveals subtle signatures of the extinct spreading ridges and FZs as well as a significant change in amplitude across the boundary between continental and oceanic crust (COBs). This is a Mercator projection; grayscale saturates at ±20 eotvos units.

sea-floor topography generated by plate tectonics such as ridges, FZs, and abyssal hills. Many FZs can now be traced much more closely to the continental margins, and one can also better interpret buried, migrating, unstable FZs, which has the potential to improve the use of FZs as tie points for reconstructions of the boundaries between continental fit reconstructions (Fig. 1). In addition to FZs, there are other tectonic features associated with continental margins, such as the boundaries between continental and oceanic crust [continent-ocean boundaries (COBs)], that can now be mapped in greater detail.

The first example (Fig. 2) is in the Gulf of Mexico, where thick sediments obscure the FZs and extinct ridges. Reconstruction models provide the overall framework of counterclockwise rotation of the Yucatan plate with respect to North America, as well as a generalized position for the COB (*9*). The new vertical gravity gradient images confirm and refine the positions of these tectonic boundaries. Extinct spreading ridges produce a negative gravity signature, because the relatively high-density sediment cover largely cancels the positive gravity effect of the topographic ridge, leaving the negative gravity signature of the compensating Moho topography (*6*). In this region, the Moho is more than 15 km beneath the sea surface, so the effects of upward continuation reduce and smooth the anomaly.

The second example is on the African ridge flank, where the new data reveal a major tectonic feature that was not visible in previous satellite gravity data sets because of high-frequency noise. The newly discovered feature is a set of tectonic lineaments roughly between 8°S and 12°S, striking northwest-southeast and obliquely dissected by individual en-echelon faults, stretching from the Bodo Verde Fracture Zone in the north into the middle of the Cretaceous Magnetic Quiet Zone at its southeastern extension (Fig. 1b). This feature

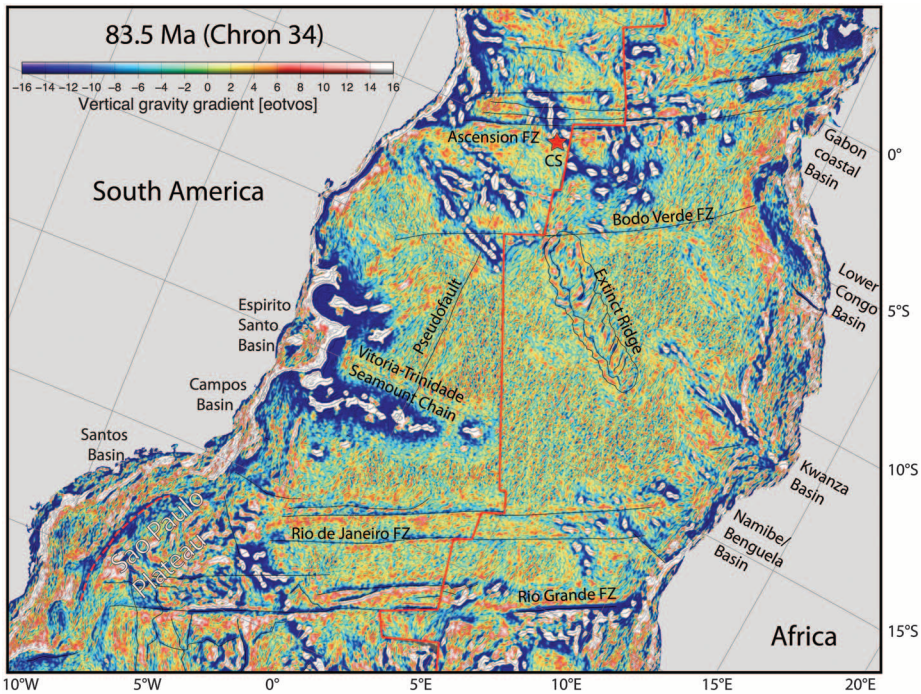

Fig. 3. South Atlantic filtered VGG. Reconstructed at chron 34 (83.5 Ma, orthographic projection) with Africa fixed (*16*). Major tectonic and volcanic sea-floor features and offshore sedimentary basins are labeled. The mid-ocean ridge is outlined in red, the extinct Abimael spreading ridge is shown as a dashed red line, and the reconstructed position of the Cardno hot spot (CS) is outlined by a red star. Most of the sea floor shown in this reconstruction was formed during the Cretaceous Normal Superchron. Also note that the extinct Abimael spreading ridge between the Santos Basin and Sao Paulo Plateau offshore of Brazil is now visible as a negative VGG anomaly (dashed red line), as compared to previous interpretations (*17*, *18*). This region is of great interest for oil and gas exploration, as it is one of the most extensive deepwater oil and gas frontiers globally, with several recent discoveries (*19*).

is about 800 km long and 100 km wide and does not follow either the azimuth of nearby sea-floor isochrons or FZs. A reconstruction of this feature at magnetic chron 34 [83.5 million years ago (Ma)] (Fig. 3) reveals that it has a mirror-image counterpart on the South American plate, but this conjugate feature is represented only by a relatively faint gravity lineament (Fig. 3). This feature is visible in the filtered vertical gravity gradient image, marking a boundary between

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swaths of differently textured sea-floor fabric to the east and west of the lineament (Fig. 3). The geometry of the two features suggests that they form a pair of an extinct ridge (on the African side) and a pseudofault (on the South American side), created by a northward ridge propagation episode between ~100 and 83 Ma. An absolute hot spot–based plate reconstruction using the rotation parameters from O'Neill *et al.* (*10*) indicates that the Cardno hot spot (Fig. 3) may have been situated not far north of the northern tip of the ridge propagator, where it abuts the Bodo Verde Fracture Zone; this is where the propagator came to a halt. These observations conform with the inference that ridges have a tendency to propagate toward hot spots/plumes and that propagation events and resulting spreading asymmetries are frequently contained within individual spreading corridors bounded by FZs (*11*). The existence of major previously unknown ridge propagation events will also be relevant for interpreting marine magnetic anomaly sequences during the Cretaceous Normal Superchron on conjugate ridge flanks (*12*).

One of the most important uses of this new marine gravity field will be to improve the estimates of sea-floor depth in the 80% of the oceans having no depth soundings. The most accurate method of mapping sea-floor depth uses a multibeam echosounder mounted on a large research vessel. However, even after 40 years of mapping by hundreds of ships, one finds that more than 50% of the ocean floor is more than 10 km away from a depth measurement. Between the soundings, the sea-floor depth is estimated from marine gravity measurements from satellite altimetry (*13*). This method works best on sea floor where sediments are thin, resulting in a high correlation between sea-floor topography and gravity anomalies in the 12-km–to–160-km wavelength band. The shorter wavelengths are attenuated because of Newton's inverse square law, whereas the longer wavelengths are partially cancelled by the gravity anomalies caused by the isostatic topography on the Moho (*13*). The abyssal hill fabric created during the sea-floor spreading process has characteristic wavelengths of 2 to 12 km, so it is now becoming visible in the vertical gravity gradient (VGG) models, especially on the flanks of the slower-spreading ridges (*14*). Additionally, seamounts between 1 and 2 km tall, which were not apparent in the older gravity models, are becoming visible in the new data. As CryoSat-2 continues to map the ocean surface topography, the noise in the global marine gravity field will decrease. Additional analysis of the existing data, combined with this steady decrease in noise, will enable dramatic improvements in our understanding of deep ocean tectonic processes.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/346/6205/65/suppl/DC1
Supplementary Text
Figs. S1 and S2
References (*20–33*)

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NANOPHOTONICS

Chiral nanophotonic waveguide interface based on spin-orbit interaction of light

Jan Petersen, Jürgen Volz,* Arno Rauschenbeutel*

Controlling the flow of light with nanophotonic waveguides has the potential of transforming integrated information processing. Because of the strong transverse confinement of the guided photons, their internal spin and their orbital angular momentum get coupled. Using this spin-orbit interaction of light, we break the mirror symmetry of the scattering of light with a gold nanoparticle on the surface of a nanophotonic waveguide and realize a chiral waveguide coupler in which the handedness of the incident light determines the propagation direction in the waveguide. We control the directionality of the scattering process and can direct up to 94% of the incoupled light into a given direction. Our approach allows for the control and manipulation of light in optical waveguides and new designs of optical sensors.

The development of integrated electronic circuits laid the foundations for the information age, which fundamentally changed modern society. During the past decades, a transition from electronic to photonic information transfer took place, and nowadays, nanophotonic circuits and waveguides promise to partially replace their electronic counterparts and to enable radically new functionalities (*1–3*). The strong confinement of light provided by such waveguides leads to large intensity gradients on the wavelength scale. In this strongly nonparaxial regime, spin and orbital angular momentum of light are no longer independent physical quantities but are coupled (*4*, *5*). In particular, the spin depends on the position in the transverse plane and on the propagation direction of light in the waveguide—an effect referred to as spin-orbit interaction of light (SOI). This effect holds great promises for the investigation of a large range of physical phenomena such as the spin-Hall effect (*6*, *7*) and extraordinary momentum states (*8*) and has been observed for freely propagating light fields (*9*, *10*) in the case of total internal reflection (*11*, *12*), in plasmonic systems (*13–15*), and for radio frequency waves in metamaterials (*16*). Recently, it has been demonstrated in a cavity-quantum electrodynamics setup in which SOI fundamentally modifies the coupling between a single atom and the resonator field (*17*).

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New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure

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Editor's Summary

High-resolution tectonic solutions

Detailed topographic maps are available for only a small fraction of the ocean floor, severely limited by the number of ship crossings. Global maps constructed using satellite-derived gravity data, in contrast, are limited in the size of features they can resolve. Sandwell *et al.* present a new marine gravity model that greatly improves this resolution (see the Perspective by Hwang and Chang). They identify several previously unknown tectonic features, including extinct spreading ridges in the Gulf of Mexico and numerous uncharted seamounts.

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