west of 153° 20′ E including the D'Entrecasteaux islands and the Goodenough basin (Fig. 1) originated in Palaeogene times as an intra-oceanic arc accommodating northerly directed subduction[7,8]. The subducting plate included a continental fragment, the Papuan plateau, which had become detached from the margin of Australia by the opening of the Coral Sea basin[9]. When the Papuan plateau encountered the trench it was partially subducted[9], and island arc ophiolite was obducted onto it[7,10]. Northward subduction ceased and subduction later reversed[11]. Southward subduction along the Trobriand trough led to arc magmatism throughout Miocene–Holocene times[12].

Sea-floor spreading in the easternmost Woodlark basin initiated by 6 Myr ago, and rifting around the D'Entrecasteaux islands had begun by Pliocene times[12] (Fig. 1). A seismic receiver function study[13] indicates that the crust thins from 32–43 km beneath the Papuan peninsula to 20–26 km beneath the Goodenough basin and D'Entrecasteaux islands. On the D'Entrecasteaux islands, pressure–

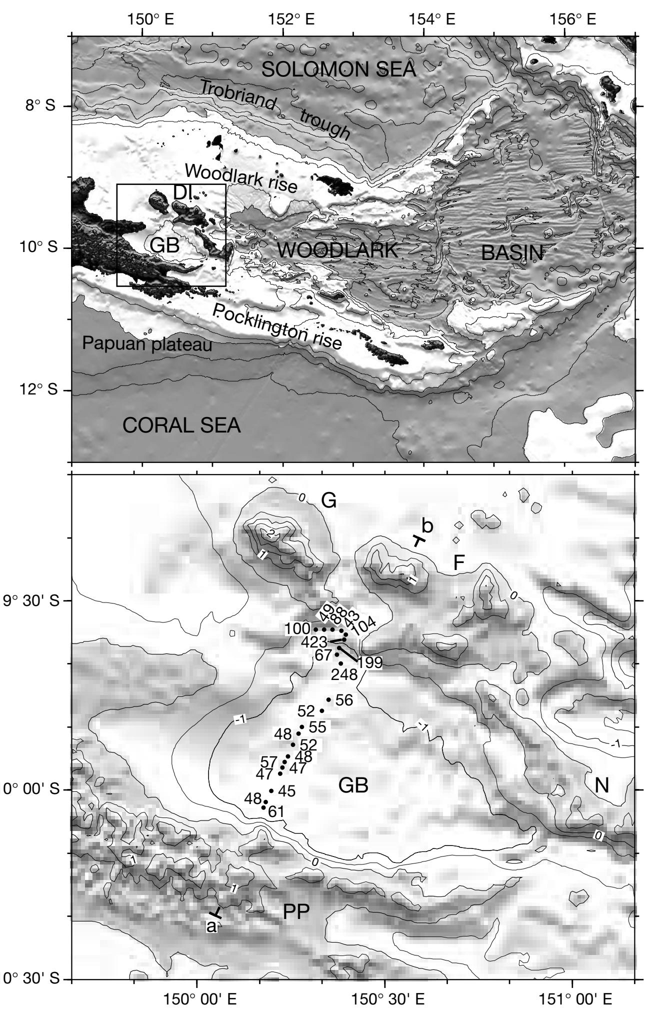


**Figure 1** The eastern Papuan peninsula has been undergoing extension since at least 6 Myr ago. Top, sea-floor spreading in the oceanic Woodlark basin split the palaeo-peninsula to form the Woodlark and Pocklington rises as rifted margins. Extension decreases westwards. Continental rifting continues in the Goodenough basin and D'Entrecasteaux islands. Bottom, details of the study area indicated by the box in the top panel. Shown are the locations of the heat-flow measurements and their values (in mW m$^{-2}$) uncorrected for sedimentation. Also shown are bathymetry and topography with contours at 500-m intervals annotated every kilometre. Abbreviations: DI, D'Entrecasteaux islands; GB, Goodenough basin; G, Goodenough island; F, Fergusson island; N, Normanby island; PP, Papuan peninsula. 'a–b' indicates modelled section shown in Fig. 4.

# Metamorphic core complex formation by density inversion and lower-crust extrusion

**Fernando Martinez*, Andrew M. Goodliffe* & Brian Taylor†**

** Hawaii Institute of Geophysics and Planetology, † Department of Geology and Geophysics, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, Hawaii 96822, USA*

**Metamorphic core complexes are domal uplifts of metamorphic and plutonic rocks bounded by shear zones that separate them from unmetamorphosed cover rocks[1]. Interpretations of how these features form are varied and controversial, and include models involving extension on low-angle normal faults[2], plutonic intrusions[3] and flexural rotation of initially high-angle normal faults[4]. The D'Entrecasteaux islands of Papua New Guinea are actively forming metamorphic core complexes located within a continental rift that laterally evolves to sea-floor spreading[5]. The continental rifting is recent (since ~6 Myr ago)[5], seismogenic[6] and occurring at a rapid rate (~25 mm yr$^{-1}$)[5]. Here we present evidence—based on isostatic modelling, geological data and heat-flow measurements—that the D'Entrecasteaux core complexes accommodate extension through the vertical extrusion of ductile lower-crust material, driven by a crustal density inversion. Although buoyant extrusion is accentuated in this region by the geological structure present—which consists of dense ophiolite overlaying less-dense continental crust—this mechanism may be generally applicable to regions where thermal expansion lowers crustal density with depth.**

The tectonic evolution of eastern Papua New Guinea created a crustal density inversion central to the proposed mechanism of core complex formation. The region of the palaeo-Papuan peninsula temperature–time studies of metamorphic minerals[14,15] show that the cores of the islands were rapidly unroofed, rising to the surface from >10 kbar (~35 km depth) since about 4 Myr ago and cooling rapidly from initial temperatures of 570–730 °C. Although the islands lie within the seismogenic rift zone[6] and within the region of crustal thinning[13], they have undergone uplift rather than subsidence. Uplift continues to the present day[15], forming topographic culminations reaching 1,500–2,500 m above sea level. In contrast, the Goodenough basin has subsided contemporaneously with the uplift of the islands, although seismic reflection studies[16] indicate insufficient normal faulting to account for the degree of subsidence.

The rising metamorphic cores of the D'Entrecasteaux islands breached cover rocks including Palaeogene ophiolite and more recent volcanics and sediments[8,17]. On the Papuan peninsula the ophiolite has an average thickness of ~15 km, including an 8–10-km-thick layer of basalt and gabbro and a 4–8-km-thick layer of harzburgite[10]. A similar crustal structure is supported regionally offshore: seismic refraction measurements[18] from a line of shots across the northern coast of the Papuan peninsula (at Killerton station) find high seismic velocities (6.86–7.96 km $s^{-1}$) overlaying a deeper layer having lower velocities (6.5 km $s^{-1}$). ODP Leg 180[19] recovered Palaeocene[20] gabbro and diabase in the area east of the D'Entrecasteaux islands, and oil-industry wells north of the islands also encountered Palaeocene ophiolite[21]. Bouguer gravity anomalies form relative lows over the islands[22], which—together with seismic evidence precluding crustal roots[13]—indicates that the islands form low-density regions surrounded by higher-density crust. Thus, we infer that except over the islands where the cover rocks have been largely stripped off, the regional crustal structure consists of ophiolite overlaying metamorphic and plutonic continental crust (Fig. 2).

This crustal structure provides a mechanism for producing both uplift and subsidence within an area undergoing overall crustal thinning. Adopting typical density values for ophiolite (3,100 kg $m^{-3}$) and continental crust (2,700 kg $m^{-3}$) creates an inverted density structure. Isostatically, if the 15-km-thick ophiolite layer were to be breached, the lower crustal layer could be extruded to a height of 2.2 km relative to the top of the ophiolite (Fig. 3a). Flow of lower crust from beneath the area would contribute to overall crustal thinning and subsidence without corresponding faulting, thinning and heating of the upper layer.

In order to examine these effects more quantitatively, we numerically modelled the thermal structure and isostatically predicted elevations for various forms of extension, and compared them to heat-flow measurements and topography. In a young rift undergoing rapid extension, a significant heat-flow anomaly can be produced that is sensitive to the pattern of lithospheric and crustal thinning. We made heat-flow measurements across Goodenough basin, from offshore of the Papuan peninsula to near Fergusson island (Fig. 1; see also Methods section). South of 9° 41′ S the heat-flow measurements average 51 mW $m^{-2}$ and have low variability (45–61 mW $m^{-2}$). To the north, near the island core complexes, the measurements have a distinctly higher average (147 mW $m^{-2}$) and greater variability (43–423 mW $m^{-2}$). Accounting for topographic effects and sedimentation following standard methodologies[23,24] increases average values south of 9° 41′ S to 73 mW $m^{-2}$ and to the north near the islands to 190 mW $m^{-2}$. Small Quaternary volcanic centres occur on the D'Entrecasteaux islands[8], and sea-floor side-scan sonar imagery and multi-channel seismic profiles[16,25] suggest small intrusions in the offshore area of the northern heat-flow measurements. These volcanic features and the higher and more variable heat flow imply a significantly higher thermal regime near the islands compared to the basin to the south.

An estimate of the crustal and lithospheric thickness and heat flow before the formation of the islands can be made by adopting a thickness of 40 km and a temperature of 700 °C for the base of the crust before 4 Myr ago—these values are consistent with the metamorphic pressure–temperature–time studies on the islands[14,15], and with seismic estimates[13] of the crustal thickness today on the Papuan peninsula. These values give a heat flow of 56 mW $m^{-2}$ and a lithospheric thickness of ~74 km, assuming a

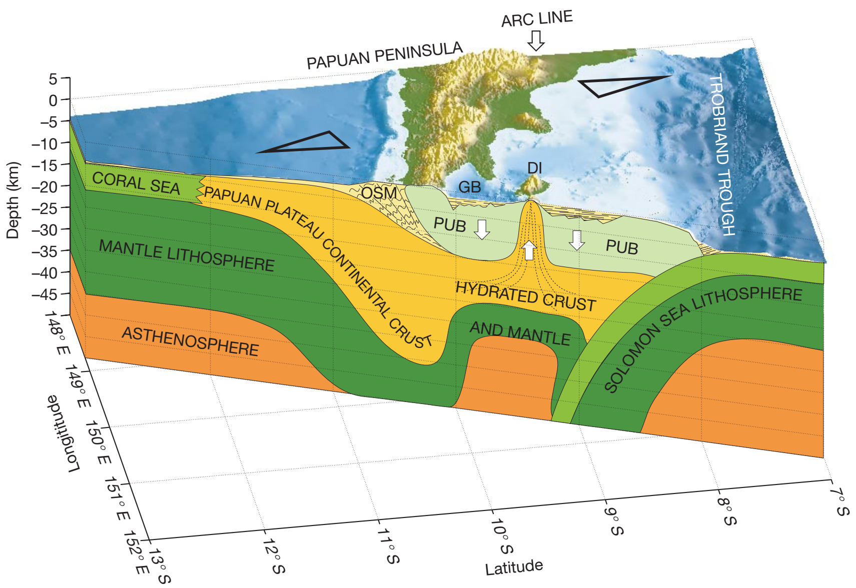


**Figure 2** Schematic interpretation of the present-day crustal structure along the heat-flow profile extended from the Coral to Solomon seas. A Palaeogene arc–continent collision emplaced the Papuan ultramafic belt (PUB), an ophiolite sequence, over the Papuan plateau, a continental fragment of Australia and cover sediments that now form the Owen Stanely metamorphic (OSM) belt on the peninsula. Arc reversal led to the Solomon Sea subducting southward along the Trobriand trough. The current overall extension direction is indicated by triangles. The D'Entrecasteaux islands metamorphic core complexes formed when the PUB was breached and pulled apart by the regional extension, allowing the lower ductile continental crust to be extruded by the weight of the overlaying PUB. Flow of the lower crust led to its preferential thinning and subsidence in the Goodenough basin (GB). Heat associated with the arc line and hydration of the lower crust and mantle by fluids from the subducting Solomon Sea plate locally weakened this area, permitting the lower crust to flow. Moho relief beneath the cold forearc and Papuan peninsula outside of this area is maintained by the stronger crust and mantle there.

linear geotherm, lithospheric conductivity of 3.2 W m$^{-1}$ °C$^{-1}$ and an asthenospheric temperature of 1,300 °C. We used two numerical techniques to model the two-dimensional, time-dependent thermal evolution and crustal and lithospheric thinning since 4 Myr ago. In the first technique[26,27], values of lower lithospheric extension ($\beta$) and upper lithospheric extension ($\delta$) are specified separately. In the second, a finite-difference method[28] is used to calculate the thermal structure for a specified geometry of pure shear extension. Thermal diffusivity is $1 \times 10^{-6}$ m$^2$ s$^{-1}$ in both cases. We first model uniform pure shear lithospheric extension by a factor of 1.6, which thins the crust from 40 km beneath the peninsula to 25 km beneath the basin and islands, and predicts heat flow of ~90 mW m$^{-2}$ in the basin. The significantly lower measured and corrected heat flow in most of the basin thus argues against uniform pure shear extension. Assuming the same starting conditions, but using a value of $\beta = 2.5$ for the crust and lithosphere beneath the 15-km-thick ophiolite layer, and using $\delta = 1$ (no extension) for the ophiolite layer, also results in an overall crustal thinning from 40 km to 25 km. In this case, however, a lower heat flow in the basin interior of 74 mW m$^{-2}$ results, due primarily to a time lag for heat to conduct across the upper unthinned layer. This lower value is more consistent with the sedimentation-corrected heat-flow values. An aspect of two-layer stretching is that it does not conserve volume[26], and in our implementation of this method the use of symmetry about the D'Entrecasteaux islands augments this artefact. The lack of two-dimensional across-axis volume conservation in problems involving lower crustal flow may, however, reflect actual three-dimensional flow. Neither uniform pure shear of the entire crust nor two-layer extension by itself, however, predicts the uplift of the islands.

We investigate the formation of the islands using the second technique. We model the splitting and separation of the upper 25 km of crust within a narrow zone (4 km) of pure shear deformation overlaying a 700 °C isothermal ductile lower crust which can flow into the space created. The initial temperature profile in the upper 15 km is varied so that the area outside of the zone of pure shear extension matches the two-layer extension result at 4 Myr. Because the zone of stretching is narrow, the upper dense ophiolite layer is quickly thinned and replaced by hot, less-dense, lower continental crust. Rapid isostatic uplift of the islands results primarily from the compositional density contrast of the layers, but there is also a smaller component of thermal uplift (Fig. 3b)

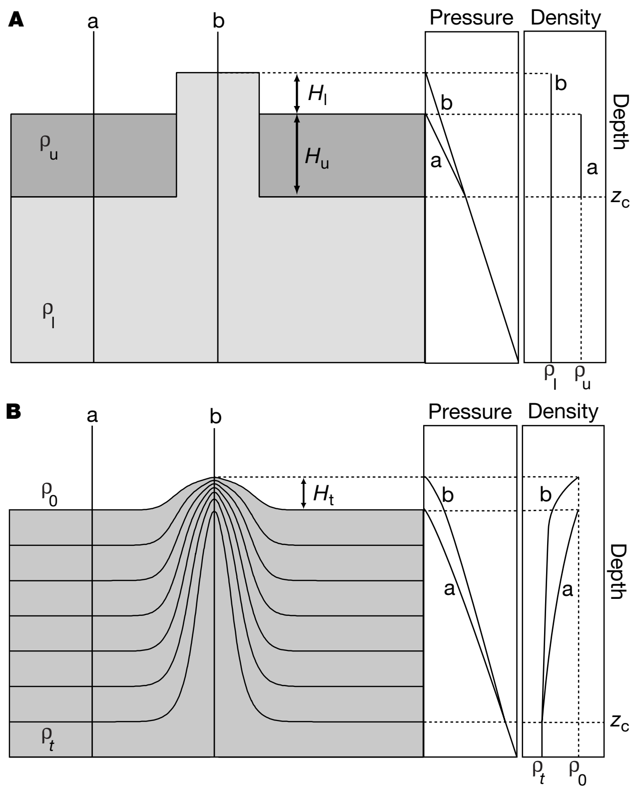


**Figure 3** Isostatic model of lower crustal flow and extrusion driven by density inversion and localization of extension. **A**, Compositionally stratified crust in which an upper layer with density $\rho_u$ greater that that of a lower layer $\rho_l$ is stretched, forming a break in the upper layer. The lower layer is extruded and rises to a height $H_l$ such that the pressure of the two columns, a and b, at $z_c$, the compensation depth, are equal: $g\rho_l(H_l + H_u) = g\rho_u H_u$, where $g$ is the acceleration of gravity. Panels at right show the variation in pressure and density with depth for the two columns, a and b. **B**, Constant-composition crust in which the density at temperature $t$, $\rho_t$, is related to the density at 0 °C, $\rho_0$, by thermal expansion coefficient, $\alpha$, following $\rho_t = \rho_0(1 - \alpha t)$. Column a has a background linear increase in temperature with depth. Column b is located at the centre of the narrow area undergoing pure shear extension. The low-density, hot lower layer has been rapidly extruded. As column b has lower density than column a above the compensation depth ($z_c$) it rises a height $H_t$ to achieve isostatic equilibrium.

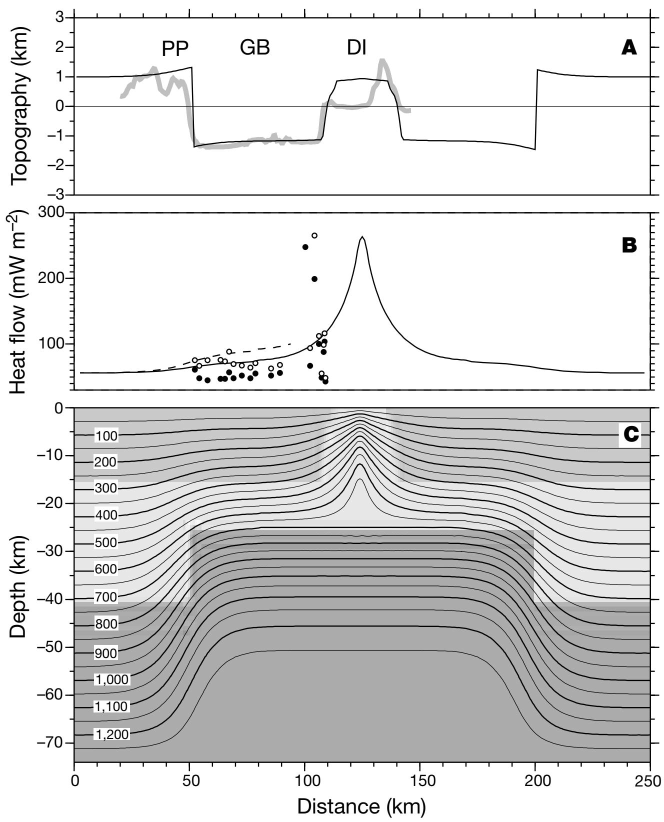


**Figure 4** Two-dimensional, time-dependent thermal calculations combining the effects of two extension calculations. **A**, Predicted topography (solid line) and observed topography (grey line) along the heat flow traverse in the Goodenough basin (GB) extended to the Papuan peninsula (PP) and D'Entrecasteaux islands (DI) (a–b in Fig. 1b). **B**, Predicted heat flow (solid line), measured heat flow (filled circles) and heat flow corrected for sedimentation and topographic effects (open circles). Dashed line shows the higher heat flow predicted by the uniform pure shear extension calculation relative to the two-layer extension. **C**, Composite crustal geometry showing the upper ophiolite layer (intermediate grey), lower continental crust (light grey), mantle (dark grey) and thermal structure after 4 Myr of extension. Extension geometries and other parameters are discussed in the text. Finite difference calculations for the core complex formation were merged between horizontal distance 80–170 km and depth 0–25 km. The area of high topography between 200 and 250 km is an artefact of model symmetry centred on the D'Entrecasteaux islands, and is not intended to model the forearc area.

which increases over the 4 Myr of extension due to heat advecting into the crustal section undergoing stretching.

We combined the thermal structures resulting from the two-layer and finite-difference thermal calculations, along a section where they predicted essentially the same crustal temperatures and heat flow (within $1\,\mathrm{mW\,m^{-2}}$). This thermal structure was then combined with the predicted crustal compositional geometry to calculate densities and the isostatically balanced topography. Densities (at 0 °C) of 3,100, 2,700, and $3,300\,\mathrm{kg\,m^{-3}}$ were used for the ophiolite, lower continental crust, and mantle, respectively, with a uniform thermal expansion coefficient of $3.4 \times 10^{-5}\,°\mathrm{C}^{-1}$. The results (Fig. 4) show that the seismically determined overall crustal thinning beneath the basin and islands can be achieved by thinning the lower crustal layer, and that this is consistent with basin subsidence and heat flow. Simultaneous breaching of the upper layer and buoyant extrusion of lower crust can explain the elevation of the core complexes relative to the basin, and also produces a distinct heat flow 'high' in their vicinity in broad agreement with thermal measurements.

These calculations are intended to illustrate general features of the proposed mechanisms of core complex formation by lower crustal flow and buoyant extrusion rather than constitute a rigorous modelling of the details of this area. We summarize below these features and their more general implications for continental rifting.

(1) Geological and geophysical observations indicate that the regional crustal structure surrounding the D'Entrecasteaux islands consists of ophiolite overlaying less-dense continental crust, creating a two-layer inverted crustal density profile.

(2) Overall crustal thinning is seismically observed in the area of the Goodenough basin and D'Entrecasteaux islands and is necessary to explain the subsidence of the basin, but uniform crustal thinning is inconsistent with heat-flow values, estimates of extension by faulting, and relative uplift of the islands.

(3) Low heat-flow measurements in the basin interior relative to model predictions for uniform crustal thinning suggest that preferential thinning of the lower crust relative to the upper crust occurs across the basin. We infer that this thinning occurs both by stretching and by crustal flow into the core complexes.

(4) Formation of the island core complexes is explained by buoyant extrusion of ductile lower crust enabled by splitting and pulling apart of the ophiolite layer, locally focusing the regional extension. The buoyancy of the lower crust alone would not probably be sufficient to breach the stronger upper layer.

(5) Because the core complex emplacement accommodates the locally focused extension it does not generate compression, as in gravity sliding models[29], nor does it generate purely radial shearing patterns implied by models of forceful plutonic emplacement[30].

(6) A narrow zone of extension can produce very rapid vertical advection of the lower crust, and account for the nearly isothermal ascent of material followed by rapid cooling inferred from the metamorphic pressure–temperature–time studies. The rapid ascent of lower crust also produces a local heat-flow 'high' in broad agreement with the high thermal regime near the islands.

(7) Although lower crustal flow, implying a weak lower crust, is proposed to occur beneath the basin and islands, significant Moho relief, implying a strong lower crust, is nevertheless maintained between the peninsula and basin. We suggest that this dual behaviour is related to the subduction of the Solomon Sea slab (Fig. 2) that locally introduces heat associated with the arc line and hydrates the mantle and lower crust beneath the basin and islands—this makes these areas weaker than those under the peninsula and cold forearc region.

(8) The mechanism of buoyant lower crustal extrusion may occur in other areas of extension and core complex formation where earlier obduction or thrusting has emplaced layers of greater density over less dense ones (Fig. 3a). It may also occur in areas of more uniform crustal composition where increasing temperatures with depth lowers crustal density by thermal expansion (Fig. 3b). In this case a cooler and more brittle surface layer may locally rupture in extension, allowing the deeper, hotter, less dense, and plastic layer to be rapidly extruded. □

## Methods

### Heat-flow data acquisition and reduction

Heat-flow data were acquired using the 'violin bow' apparatus of the Pacific Geoscience Centre, Geological Survey of Canada; this apparatus consists of a 3-m-long sensor string enclosing 11 thermistors mounted outboard of a strength member. *In situ* conductivities were determined at each measurement site by discharging a calibrated heat pulse into the sediments. Water column temperatures across the basin were constant below ~600 m and plots of temperature versus thermal resistance in the sediments were linear, indicating no disturbances due to bottom-water temperature variation or advection in the sediments. Data were corrected for sedimentation using a six-channel seismic profile to estimate sediment thickness to acoustic basement at each heat-flow measurement site. A limit on the plausible sedimentation effects was estimated using an analytical one-dimensional solution[24], assuming that the observed thickness at each site was deposited in 1 Myr and using a sediment thermal diffusivity of $0.421 \times 10^{-6}\,\mathrm{m^2\,s^{-1}}$. Topographic corrections were estimated using a two-dimensional relaxation method[23] and the seismic profile to estimate relief on the sea floor and acoustic basement—assuming thermal conductivities of 1.2 and $2.3\,\mathrm{W\,m^{-1}\,K^{-1}}$ for sediments and acoustic basement, respectively.

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Correspondence and requests for materials should be addressed to F.M. (e-mail: martinez@soest.hawaii.edu).