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An explanation for the age independence of oceanic elastic thickness estimates from flexural profiles at subduction zones, and implications for continental rheology

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A B S T R A C T

Most properties of oceanic lithosphere are widely observed to be dependent on the age of the plate, such as water depth, heat flow, and seismogenic thickness. However, estimates of the 'effective elastic thickness' of oceanic lithosphere based on the deflection of the plate as it enters a subduction zone show little correlation with the age of the incoming lithosphere. This paradox requires reconciliation if we are to gain a full understanding of the structure, rheology, and behaviour of oceanic lithosphere. Here, we show that the permanent deformation of the plate due to outer-rise faulting, combined with uncertainties in the yield stress of the lithosphere, the in-plane forces transmitted through subduction zones, and the levels of noise in bathymetric and gravity data, prevents simple elastic plate modelling from accurately capturing the underlying rheological structure of the incoming plate. The age-independent estimates of effective elastic thickness obtained by purely elastic plate modelling are therefore not likely to represent the true rheology of the plate, and hence are not expected to correspond to the plate age. Similar effects may apply to estimates of elastic thickness from continental forelands, with implications for our understanding of continental rheology.

1. Introduction

Constraining the mechanical properties of the lithosphere is important for understanding how it supports and transmits stress, and also the controls on the location and characteristics of deformation. The influence of composition and layering on lithospheric strength in the continents remains a controversial topic (e.g. Jackson et al., 2008; Burov, 2010). However, oceanic lithosphere should represent a case in which there is relatively little variation in composition, either vertically or laterally. The rheological structure of the plate is believed to be composed of a single strong layer at the top of the plate, underlain by much weaker material beneath. Numerous studies have tried to estimate the 'effective elastic thickness' (T_e) of oceanic lithosphere (the thickness of the layer within the plate capable of supporting elastic stresses over geological timescales – hereafter referred to as the elastic thickness) from the deflection of the incoming oceanic plate into subduction zones, as observed in either bathymetric or gravitational data (e.g., McNutt, 1984; McQueen and Lambeck, 1989; Levitt and Sandwell, 1995; Bry and White, 2007; Contreras-Reyes and Osses, 2010, see also Fig. 1). The loading of the incoming oceanic plate by the overriding forearc, along with the negative buoyancy of the downgoing oceanic lithosphere, causes the plate to bend down into the subduction zone. The rheological properties of the plate control the width and amplitude of the trench itself, along with the wavelength and amplitude of bathymetric features further seawards including the outer rise (see Fig. 2).

Many of the observable properties of oceanic lithosphere show a general dependence on the age of the lithosphere, and are therefore likely to be related to the thermal structure of the plate. The subsidence of the seafloor, the surface heatflow, the seismological structure of the plate, and its seismogenic thickness, all show a general correlation to the plate age (Parsons and Sclater, 1977; Wiens and Stein, 1983). The seismogenic thickness is expected to be a similar indicator of the mechanical strength of the plate to the elastic thickness (at least in terms of general trends), as both are strongly dependent on the thermal structure of the lithosphere, regardless of where within the lithosphere the plate-driving forces are supported. Given the direct correspondence seen between plate age and seismogenic thickness (Wiens and Stein, 1983; McKenzie et al., 2005; Craig et al., 2014), a similar age dependence might be expected from estimates of the elastic thickness.

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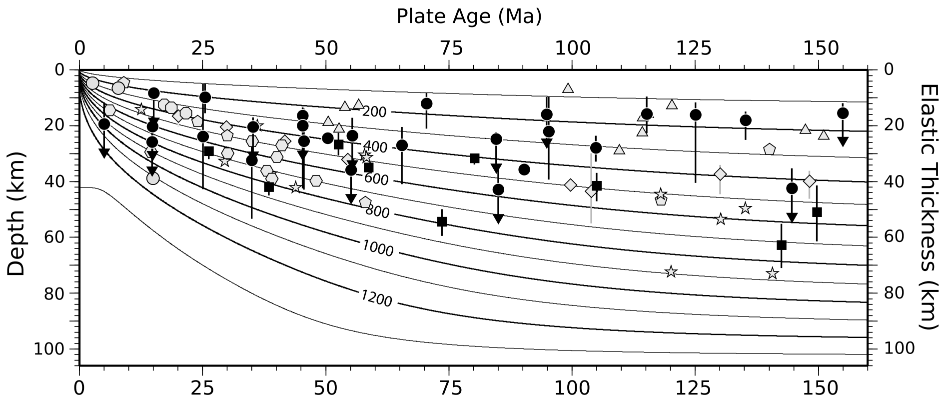

Fig. 1. Elastic thickness measurements from published studies using trench flexure, and thermal structure as a function of plate age. Diamonds are from McNutt (1984), squares are from McAdoo et al. (1985), triangles are from McQueen and Lambeck (1989), stars are from Levitt and Sandwell (1995), circles are from Bry and White (2007), hexagons are from Contreras-Reyes and Osses (2010), and octagons from Chang et al. (2012). Black points are those estimates derived from modelling profiles stacked along-strike for a wide region. Grey points are those derived from modelling individual bathymetry or gravity profiles. Error bounds, where estimated are shown, with small black triangles indicating that the maximum values are unconstrained. All error bars are large enough to be seen – for points with no visible error bar, no error estimate was given. Isotherms are calculated using the model of McKenzie et al. (2005) for a plate 106 km thick and a mantle potential temperature of 1315 °C. The vertical axis corresponds to depth within the plate for the thermal structure, and elastic thickness for the modelled elastic thickness points.

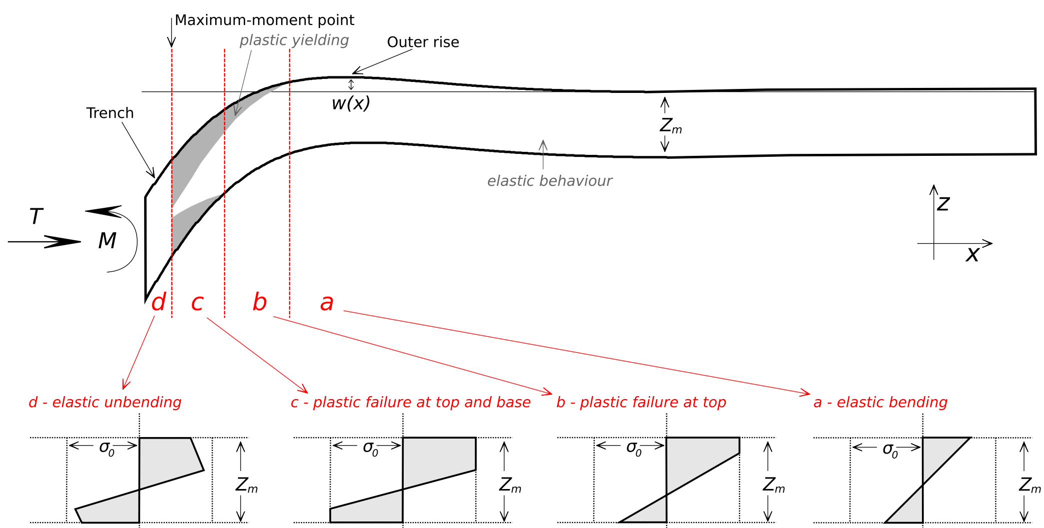

Fig. 2. Sketch of modelling setup. The model is for an elastic–plastic plate. Grey shaded regions indicate parts of the plate undergoing plastic deformation, with an overall in-plane extensional force. Dashed red lines separate different deformation regimes, as indicated by the related stress profiles (a)–(d). T is the in-plane force, M the bending moment, $w(x)$ the plate deflection, and z_M the plate thickness. (a) Stress profile for elastic bending, with σ_0 indicating the yield stress. (b) Stress profile for elastic bending with plastic failure at the top of the plate. (c) Stress profile for elastic bending with plastic failure at the top and base of the plate. (d) Stress profile for elastic unbending. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Previous observations of elastic thickness

A compilation of studies that have estimated the elastic thickness of oceanic lithosphere, based on the deflection of the plate at oceanic trenches observed using either bathymetric or gravitational profiles, is shown in Fig. 1 (see figure caption for the sources of these estimates). As this compilation demonstrates, individual estimates of the elastic thickness show no direct correspondence with the age of the plate where the measurements were made. For example, some estimates of the elastic thickness from trenches where the downgoing plate age is ∼150 Ma are as low as 15 km, whilst some based on trenches where the downgoing plate age is ∼25 Ma are as high as 30 km. This lack of age dependence holds true even when comparing estimates derived using the same data, and the same technique, from the same study. This paper seeks to understand why individual estimates of the elastic thickness from oceanic trenches show such little dependence on plate age, in contrast to other indicators of plate structure and rheology. Such an explanation is important for understanding the way in which the lithosphere supports applied stresses, and how these are reflected in the deformation of the plate.

Previous estimates of the elastic thickness in the oceans have relied upon modelling the deflection of the plate under an applied load – either a seamount or at an oceanic trench. However, in order to make an estimate of the mechanical properties of the plate, a rheology must be assumed. Bathymetric and gravitational profiles have been shown to be insufficient to distinguish between different rheological models for oceanic lithosphere, with different combinations of elastic, elastic–plastic and viscous responses all able to fit the deflection data equally well (Chapple and Forsyth, 1979; Forsyth, 1980). The occurrence of earthquakes associated with the bending of the plate at the outer rise (e.g. Stauder, 1968; Chapple and Forsyth, 1979; Craig et al., 2014) indicates that the process of plate flexure in this setting it not purely elastic, but involves the brittle failure of the plate resulting in permanent deformation. This brittle failure of the plate in earthquakes is commonly treated in modelling studies as the bulk plastic, rather than elastic, deformation of the plate at points exceeding