Inelastic models of lithospheric stress—II. Implications for outer-rise seismicity and dynamics

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SUMMARY
Outer-rise seismicity and dynamics are examined using inelastic models of lithospheric deformation, which allow a more realistic characterization of stress distributions and failure behaviour. We conclude that thrust- and normal-faulting outer-rise earthquakes represent substantially different states of stress within the oceanic lithosphere. Specifically, the normal-faulting events occur in response to downward plate bending, which establishes the ‘standard’, bending-dominated state of outer-rise stress, and the thrust-faulting events occur in response to an elevated level of in-plane compression, which develops only in response to exceptional circumstances. This interpretation accounts for the observation that normal-faulting outer-rise earthquakes occur more frequently and are more widely distributed than their thrust-faulting counterparts, an observation for which the simple bending model offers no explanation. In addition, attributing both thrust- and normal-faulting outer-rise earthquakes to plate bending implies that both classes of events should occur within relatively close lateral proximity to one another because both are allegedly a manifestation of the same bending-dominated stress distribution, whereas, in reality, this is not observed. We propose that the tendency for thrust-faulting outer-rise earthquakes to exhibit greater source depths than their normal-faulting counterparts (an observation that is frequently cited in support of the bending interpretation of the former) is merely a consequence of the fact that bending-induced tension is confined to the upper lithosphere. Our model predicts that outer-rise in-plane-force variations may promote thrust-faulting outer-rise activity prior to an underthrusting interplate subduction earthquake and normal-faulting outer-rise activity following such an earthquake, but that both forms of outer-rise activity are unlikely to be associated with the same subduction earthquake. A corollary implication of our model is that subduction earthquakes are likely to be either preceded by or followed by an absence of large outer-rise earthquakes. Levels of in-plane compression necessary to generate thrust-faulting outer-rise earthquakes are attributed to stress concentrations within the subducting plate that are induced by relatively localized resistance to regionally distributed plate-driving forces. Resistance of this nature may result from either the attempted subduction of relatively buoyant (i.e. isostatically compensated) bathymetric features or the existence of strong interplate asperities.

Key words: lithospheric deformation, plate convergence, seismicity, subduction.

1 INTRODUCTION
A characteristic feature of subduction zones is the occurrence of relatively shallow normal-faulting earthquakes within the subducting plate in the vicinity of the trench axis. Stauder (1968) concluded that these earthquakes, which typically exhibit focal mechanisms indicative of tension oriented orthogonally to the trench axis, were triggered by the downward plate bending within the outer-rise complex that is necessary to accommodate subduction into the trench. Although thrust-faulting earthquakes also occur within some outer-rise regions, they are quite rare. On average, approximately one per year is confirmed teleseismically (Christensen & Ruff 1988). Chen & Forsyth (1978) and Chapple & Forsyth (1979) proposed
that thrust-faulting outer-rise earthquakes were also triggered by plate bending within the outer-rise complex, which induces compression within deeper portions of the oceanic lithosphere. Chapple & Forsyth (1979) presented evidence that thrust-faulting outer-rise earthquakes are characterized by a greater average source depth than normal-faulting outer-rise earthquakes, an observation that is intuitively consistent with the bending interpretation of both classes of outer-rise events.

Attributing both thrust- and normal-faulting outer-rise events to the same mechanism cannot directly account for the important observation that the former occur much less frequently than the latter. Physical insight into the predominance of normal-faulting activity was offered by Christensen & Ruff (1988), who noted that thrust-faulting outer-rise events are restricted to subduction zones that are characterized by relatively large interplate underthrusting earthquakes. These interplate events, which we will refer to as subduction earthquakes, are believed to be triggered by the failure of a region (or regions) of enhanced coupling between the underthrusting and overriding plates. Such regions are referred to as subduction-zone asperities. Considering the restrictive nature of thrust-faulting outer-rise seismicity, it is plausible to assume that the generation of these earthquakes is somehow associated with the existence of subduction-zone asperities.

Thrust-faulting outer-rise earthquakes occasionally precede nearby subduction earthquakes by several years. Christensen & Ruff (1983, 1988) proposed that the former are triggered by a combination of plate bending and the accumulation of in-plane compression that may be associated with the rupture of subduction-zone asperities. Because this interpretation implies that thrust-faulting outer-rise earthquakes represent precursory seismic activity to subduction earthquakes, Christensen & Ruff (1988) suggested that thrust-faulting activity within the outer rise may be useful in assessing the intermediate-term seismic hazard for potentially destructively subduction earthquakes. Subduction earthquakes are also sometimes followed by normal-faulting outer-rise activity. Christensen & Ruff (1988) inferred the existence of an outer-rise 'earthquake cycle', in which in-plane-force variations associated with the occurrence of subduction earthquakes establish the potential for thrust-faulting activity before, and normal-faulting activity after, a subduction earthquake.

It is important to emphasize that Christensen & Ruff (1983, 1988) attributed thrust-faulting outer-rise earthquakes to a combination of in-plane compression and plate bending. In fact, their qualitative interpretive model assumed that the stress distribution was dominated by plate bending and that minor variations in the level of in-plane force governed the timing of outer-rise seismic activity. The dominant influence of plate bending implies a relatively small level of in-plane force. Recent investigators who have also attributed a predominant role to plate bending in the generation of thrust-faulting outer-rise earthquakes include Ward (1983, 1984), Dmowska & Lovison (1988), Dmowska et al. (1988), Seno & Honda (1988), Honda, Kawakatsu & Seno (1990), Tichelaar, Christensen & Ruff (1992), and Liu & McNally (1993). The majority of researchers who have addressed thrust-faulting outer-rise earthquakes have attributed these events to the compression that is induced in the lower oceanic lithosphere by downward plate bending.

We utilize inelastic models of lithospheric stress to demonstrate that thrust- and normal-faulting outer-rise earthquakes probably reflect substantially different states of stress within the outer-rise complex. Although our model supports Stauder's (1968) interpretation that normal-faulting outer-rise earthquakes occur in response to bending-induced tension within the shallow oceanic lithosphere, it is inconsistent with the ostensibly intuitive notion that thrust-faulting outer-rise earthquakes are a consequence of bending-induced compression within the lower oceanic lithosphere. Using inelastic models of lithospheric stress distributions, we demonstrate that downward plate bending can neither induce nor enhance compressional failure within the brittle (i.e. potentially seismogenic) portion of the oceanic lithosphere. We further propose that a bending-dominated stress distribution, which promotes normal-faulting seismic activity, represents the 'standard' outer-rise state of stress and that conditions conducive to the development of thrust-faulting outer-rise earthquakes develop only in response to specific tectonic conditions. This interpretation of outer-rise earthquakes, in marked contrast to that based solely on plate bending, readily accounts for the observed predominance of normal-faulting activity.

2 OUTER-RISE SEISMICITY

2.1 Normal-faulting outer-rise earthquakes

In this section, we examine the factors associated with the occurrence of normal-faulting outer-rise earthquakes. Since Stauder (1968), it has been generally accepted that normal-faulting outer-rise earthquakes are a manifestation of tensional failure induced by the downward plate bending that is necessary to accommodate subduction into the trench. Because the bending-induced tension occurs within the relatively shallow, brittle portion of the oceanic lithosphere, this interpretation is entirely consistent with the consensus among rock mechanists that only brittle lithospheric failure is potentially seismogenic (e.g. Scholz 1990). Although the dominant contribution of outer-rise plate bending has never been seriously challenged, it has been proposed that the bending-induced tension may be supplemented by significant levels of in-plane tension associated with the plate-driving slab-pull force (Abe 1972; Spence 1977, 1987; Christensen & Ruff 1988; Dmowska et al. 1988), the magnitude of which may readily exceed $1 \times 10^{14} \text{N m}^{-1}$ (e.g. McKenzie 1969; Davies 1983).

The potential contribution of the slab-pull force to in-plane tension within the outer-rise complex is limited by slab compensation within the mantle (Davies 1981, 1983; Spence 1987). In other words, much of the excess slab weight is supported at depth by various mechanisms, which may include viscous resistance to slab descent and/or other forms of flow-induced traction at the slab-mantle interface (Davies 1981, 1983), as well as buoyancy forces associated with endothermic and kinetically inhibited exothermic phase transitions (Idaka & Suetsumugi 1992). That a significant fraction of the slab-pull force must be compensated in this manner is unequivocally demonstrated by a direct comparison of the predicted slab-pull force and estimates of net tensional lithospheric strength. For example, assuming a modest slab dip of 45° and convergence rate of 6 cm yr$^{-1}$, the slab-pull force associated with 100 Ma oceanic lithosphere is approximately $5 \times 10^{12} \text{N m}^{-1}$ (Davies 1983), whereas the relevant net tensional lithospheric strength is unlikely to exceed $1.3 \times 10^{12} \text{N m}^{-1}$ (e.g. Mueller, Choy & Spence 1996).

The uncompensated fraction of the slab-pull force (i.e. that
which is transmitted into the outer-rise complex) is of interest because it is presumably a contributing factor in the occurrence of extremely powerful and often destructive subduction earthquakes (see review by Spence 1987), which represent the sudden catastrophic slip of a subducting plate beneath the associated overriding plate. In theory, it is possible to estimate the uncompensated portion of the slab-pull force by a comparison of the observed maximum depth extent of normal-faulting outer-rise earthquakes with model-based predictions of tensile lithospheric failure that assume various levels of in-plane tension (e.g. Mueller et al. 1996, Fig. 7). In practice, however, reliable estimates are obscured by the dominance of bending-induced tensional failure over that which may be induced by in-plane tension (i.e. flexure is considerably more efficient at inducing deep tensional failure). Elevated levels of in-plane tension do increase the maximum depth to which normal-faulting outer-rise earthquakes may nucleate and/or propagate beyond that which may result from plate bending alone. Unfortunately, however, substantial differences in in-plane tension are generally associated with relatively small differences in the predicted maximum depth of tensional failure. This is evident from Fig. 1, in which this maximum depth is plotted as a function of in-plane tension for various plate curvatures.

In Fig. 1, in-plane tension is normalized to the net tensional strength of oceanic lithosphere of the relevant age (in this case, 100 Ma). The curves presented in Fig. 1 embody the assumption that the maximum depth of rupture propagation is limited by the barrier-like behaviour of the elastic core (not the idealized brittle-plastic transition) (e.g. Mueller et al. 1996). These curves are therefore terminated immediately prior to the elimination of this core, which, regardless of plate curvature and loading order, occurs when the applied in-plane force equals the net lithospheric strength. Because elaborate studies of outer-rise earthquakes (e.g. Honda et al. 1990; Tichelaar et al. 1992; Liu & McNally 1993) have been unable to determine point-source depths and/or maximum depth of rupture to an accuracy of better than ±5 km, it is unlikely that source modelling of normal-faulting outer-rise events would result in a reliable verification of the existence of an uncompensated component of the slab-pull force, unless this component were to exceed 60 per cent of the net tensional strength of unsubducted lithosphere (Fig. 1). In addition, bathymetric noise (i.e. seafloor-depth variations unrelated to outer-rise flexure) often precludes reliable estimates of plate curvature at a specified location (McNutt & Menard 1982; McQueen & Lambeck 1989), such as the epicentral region of an outer-rise earthquake.

2.2 Thrust-faulting outer-rise earthquakes

We now examine the factors associated with the occurrence of thrust-faulting outer-rise earthquakes. Although rare, thrust-faulting earthquakes occur within some outer-rise regions. On average, approximately one thrust-faulting outer-rise earthquake per year is confirmed telesismically (e.g. Christensen & Ruff 1988). These events have been routinely attributed to the bending-induced compression within the lower portion of the lithosphere. Since this interpretation was initially proposed by Chen & Forsyth (1978), it has been adopted by Chappe & Forsyth (1979), Shelton, Tullis & Tullis (1981); Ward (1983, 1984), Christensen & Ruff (1988), Dmowska & Lovison (1988), Dmowska et al. (1988), Honda et al. (1990), Seno & Honda (1988, 1990), Tichelaar et al. (1992) and Liu & McNally (1993). Although the plate-bending model remains a robust explanation for normal-faulting outer-rise earthquakes, we will demonstrate that the ability of this model to account for thrust-faulting outer-rise earthquakes is compromised by both laboratory and seismologic observations.

2.2.1 Thrust-faulting outer-rise earthquakes and lithospheric rheology

Early attempts to correlate outer-rise seismicity with the state of stress within subducting lithosphere utilized elastic models of plate deformation because that was the currently available methodology, not because it was assumed that elastically supported stress was potentially seismogenic (e.g. Chen & Forsyth 1978; Ward 1984). Unfortunately, however, not all subsequent studies have recognized this distinction. For example, in a recent analysis of outer-rise seismicity, Liu & McNally (1993) assumed that the existence of compressional stress is a wholly sufficient condition for thrust-faulting earthquakes and that the existence of tensional stress is a wholly sufficient condition for normal-faulting earthquakes.

Despite compelling evidence to the contrary, the assumption that lithospheric failure is synonymous with seismicity is frequently encountered in interpretations of outer-rise earthquakes. This is reflected in the assumption that bending-
induced compressional failure within the lower portion of the outer rise is seismogenic (e.g. Chen & Forsyth 1978; Ward 1983, 1984; Dmowska & Leovison 1988; Dmowska et al. 1988; Honda et al. 1990; Seno & Honda 1990; Tichelaar et al. 1992). Such an assumption fails to distinguish between the brittle failure that occurs within the upper portion of the plate, which is generally acknowledged to be potentially seismogenic, and the plastic failure that occurs within the lower portion of the plate (e.g. Mueller et al. 1996, Fig. 3a). The majority of rock mechanists, structural geologists and seismologists regard brittle failure as an essential, although not necessarily sufficient, condition for seismicity (e.g. Meissner & Strehlau 1982; Sibson 1982, 1984; Chen & Molnar 1983; Smith & Brunn 1984; Doser & Kanamori 1986; Miller & Furlong 1988; Scholz 1988, 1990; Evans, Fredrich & Wong 1990; Segall 1991; Chester, Evans & Biegel 1993; Tullis 1994). The single notable exception, for which there is more than isolated support for a possibly non-brittle seismic mechanism, is the concept of transformational faulting, which may be associated with phase transformations in subducting slabs (Kirby, Durham & Stern 1991). Of all the authors that have attributed thrust-faulting outer-rise earthquakes to bending-induced compression, only Chapple & Forsyth (1979) and Shelton et al. (1981) indicated that they were aware of the potential rheological difficulties.

If thrust-faulting outer-rise earthquakes are to be legitimately attributed to bending-induced compressional failure within the lower portion of the lithosphere, at least one of the following questions must be answered in the affirmative.

(1) Is lithospheric failure that is accommodated by a fully plastic mechanism potentially seismogenic?

(2) Is it possible to attribute thrust-faulting outer-rise seismicity to bending-induced semi-brittle failure?

(3) Are there conditions under which the brittle regime may extend to depths subjected to bending-induced compression?

We examine each of these questions separately.

2.2.2. Seismicity and plastic failure

Wiens & Stein (1983, 1985) and Stein & Pelayo (1991) concluded that the focal depths of some intraplate oceanic earthquakes exceed estimated depths of the brittle-plastic transition and, on this basis, proposed that a brittle rheology does not constitute a requisite condition for seismic activity. Such an inference should be regarded as questionable, however, for the following reasons.

(1) The notion that the brittle–plastic transition is abrupt, and therefore well defined, has been discredited (Kirby 1980; Scholz 1988, 1990; Rutter & Brodie 1991; Tullis & Yund 1992).

(2) Coseismic deformation is characterized by a strain rate that may exceed typical tectonic strain rates by 10 orders of magnitude (Jackson & White 1989; Evans et al. 1990). Consequently, a coseismic depression of the strain-rate dependent brittle–plastic transition (e.g. Mueller et al. 1996, Fig. 2a) will allow rupture propagation to significantly greater depths (Sibson 1980; Das 1982; Strehlau 1986; Scholz 1988, 1990).

(3) Even at constant strain rate, the predicted depth of the idealized transition is highly uncertain.

For example, Fig 2 illustrates the range of the predicted transitional depth that is associated solely with uncertainties in the lithospheric temperature distribution. The yield envelope depicted assumes a constant-diffusivity cooling-plate model with the empirically constrained thermal parameters of Stein & Stein (1992). The combined uncertainty in two of these parameters, thermal plate thickness and asthenospheric temperature (95 ± 15 km and 1450 ± 250°C; Stein & Stein 1992), results in an approximately 20 km uncertainty in the predicted depth of the idealized brittle–plastic transition for 100 Ma oceanic lithosphere (Fig. 2). This uncertainty is further compounded by the appropriate choice of a representative silicate plastic-flow law, which depends upon poorly characterized parameters, such as grain size, water content, mineralogy, and ambient strain conditions (i.e. transient versus steady state). In addition, controversy persists regarding the preferred thermal model. For example, Carlson & Johnson (1994) recently concluded that the once popular semi-infinite half-space model may have been abandoned prematurely. Although both Stein & Stein (1992) and Denlinger (1992) favour the cooling-plate model, the latter has criticized the routine assumption that the thermal diffusivity is constant. The incorporation of laboratory-derived temperature-dependent diffusivity values predicts a substantial deepening of lithospheric isotherms at intermediate depths (Denlinger 1992), and a corresponding depression of the idealized brittle–plastic transition.

Although theoretical arguments suggesting that earthquakes may be triggered by some type of purely plastic instability are occasionally propounded (e.g. Orowan 1960; Twiss 1976; Goetze 1978; Zeuch 1982; Hobbs & Ord 1988), laboratory observations that support the occurrence of stick-slip behaviour within the fully plastic regime are scarce. This is in marked contrast to an abundance of laboratory investigations that have firmly established the seismogenic potential of brittle deformation (e.g. Scholz 1990 and references therein). Post (1977) reported evidence of 'ductile faulting', characterized by gradual stress drops along relatively well-defined shear zones.
during high-temperature deformation experiments on dunite. Although, in one extreme case, the stress drop occurred within a period of approximately 10 s, a duration of several hours was typically observed (Post 1977). Because this phenomenon has not been replicated during the course of other investigations into the plastic deformation of dunite (e.g. Carter & Ave Lallemant 1970; Blacic 1972; Zeuch & Green 1979; Chopra & Paterson 1981, 1984), the suggestion that it represents a purely plastic instability should be regarded with cautious scepticism.

A similar phenomenon reported by Shelton et al. (1981) during the high-temperature high-pressure experimental deformation of albite suggests an alternative interpretation of the observations of Post (1977). The high-temperature faulting of albite was also associated with extremely gradual stress drops; in this case, however, the observation of a Coulomb-type relationship between shear strength and confining pressure (Shelton et al. 1981) unequivocally indicated the presence of a significant brittle component (Evans et al. 1990). For this reason, a plausible interpretation of the 'ductile faulting' observed by Post (1977) is that it occurred within the semi-brittle, as opposed to the fully plastic, regime. Attributing gradual stress drops that occur at elevated temperatures to semi-brittle deformation is also supported by the observation of extremely slow rupture velocities during stick-slip behaviour within the semi-brittle regime of halite gouge (Shimamoto 1985), behaviour which does not persist into the fully plastic regime (Shimamoto 1985).

2.2.3 Seismicity and semi-brittle rheology

In the previous section, we discussed the notion that a coseismic depression of the strain-rate-dependent brittle-plastic transition may allow seismic faulting to propagate into what would normally be regarded as the semi-brittle regime. In the outer-rise environment, however, a coseismic depression of this transition cannot trigger thrust-faulting earthquakes because the shallow tensional stress regime is separated from the deeper compressional stress regime by the barrier-like elastic core (e.g. Mueller et al. 1996; Fig. 3a).

Thrust-faulting outer-rise earthquakes may be directly attributed to bending-induced semi-brittle compressional failure only if it is possible for earthquakes to nucleate within the semi-brittle regime. Although fault development has been observed within the semi-brittle regime of quartz, the faulting process is not associated with an unstable stress drop (Hirth & Tullis 1994), which represents an essential condition for a seismic expression. Hirth & Tullis (1994) theorized that semi-brittle faulting within silicate materials may be stabilized by blunting of the leading edge of the fault due to the activation of intracrystalline dislocations. Shimamoto (1985) reported the occurrence of stick-slip behaviour during the semi-brittle deformation of halite, which terminated prior to the onset of full plasticity. The unusually low rupture velocities recorded (e.g. \( \approx 1 \) mm s\(^{-1}\); Shimamoto 1985), however, which are reminiscent of the extremely gradual stress drops observed by Post (1977) and Shelton et al. (1981), bear little resemblance to the dynamic characteristics of thrust-faulting outer-rise earthquakes.

The possibility that thrust-faulting outer-rise earthquakes represent semi-brittle yielding that occurs directly in response to bending-induced compression within the lower portion of the oceanic lithosphere cannot be rigorously precluded. However, in the absence of unequivocal evidence indicating that earthquake-like stick-slip behaviour is possible within the semi-brittle regime, such an interpretation must be regarded as highly speculative. Models capable of attributing thrust-faulting outer-rise events to a brittle mechanism should be preferred.

2.2.4 Unusually deep brittle regime

In theory, an extremely weak brittle rheology may depress the idealized brittle-plastic transition sufficiently so that it is located within the compressional regime of a bending-induced stress distribution. Only in this manner is it possible to promote compressional brittle failure in response to outer-rise-type bending, although, even under these conditions, relatively high values of plate curvature are necessary. This is illustrated in Fig. 3(a), in which the brittle strength of 100 Ma oceanic lithosphere is reduced dramatically by the assumption that the ambient pore pressure is equivalent to 99 per cent of the
lithostatic (i.e. rock overburden) pressure. A rather high value of plate curvature ($1 \times 10^{-6} \text{m}^{-1}$) was also assumed (this is evident in the nearly horizontal stress distribution within the elastic core). Under these extreme conditions, it is marginally possible for bending-induced compressional failure to enter the brittle field, as defined by the depth of the idealized brittle-plastic transition (Fig. 3a).

A number of difficulties render this scenario highly unlikely. The predicted strength of such 'overpressured' oceanic lithosphere is two orders of magnitude less than conventional estimates (e.g. McNutt & Menard 1982; McDaido, Martin & Poulose 1985; Wessel 1992). This is illustrated in Fig. 3(b), in which the lithospheric yield envelope of Fig. 3(a) is depicted at the same scale as the 'standard lithospheric yield envelope' specified by Mueller et al. (1996, Fig. 1). Because the outer-rise flexural bulge is a manifestation of lithospheric strength, it is difficult to reconcile the mere existence of an outer-rise complex with the notion that the oceanic lithosphere is as weak as depicted in Fig. 3(a). Flexural models of lithospheric deformation indicate that observed outer-rise widths and heights are consistent with conventional estimates of lithospheric strength (e.g. Goetze & Evans 1979; Bodine, Steckler & Watts 1981; McDaido et al. 1985). Also, a bending moment of $-1.4 \times 10^{28} \text{N}$ is implied by the stress distribution depicted in Fig. 3(a), which, despite the relatively extreme plate curvature, is two to three orders of magnitude less than estimates based on flexural modelling of outer-rise bathymetry (Goetze & Evans 1979; Bodine et al. 1981).

2.3 Distribution of outer-rise earthquakes

The greatest appeal of the plate-bending model as an explanation for thrust-faulting outer-rise earthquakes is its simplicity, and, in its simplest form, this interpretation implies that thrust- and normal-faulting outer-rise events should occur within close proximity to one another because both are induced by the same bending-dominated stress distribution. This interpretation also implies that, in the absence of extreme values of plate curvature, depth distributions of thrust- and normal-faulting earthquakes should be distinctly separated by a few tens of kilometres, and that thrust-faulting ruptures cannot propagate upwards into the shallow portion of the lithosphere. Both of these depth-related constraints are a consequence of the barrier-like behaviour of the elastic core (e.g. Mueller et al. 1996, Fig. 3a). The plate-bending interpretation of thrust-faulting outer-rise earthquakes implies a number of straightforward predictions regarding the distribution, both lateral and vertical, of outer-rise seismicity, which we now examine.

2.3.1 Lateral distribution

The locations of circum-Pacific outer-rise earthquakes teleseismically identifiable as either thrust- or normal-faulting in nature are illustrated in Fig. 4. This figure reveals that these earthquakes are not randomly distributed. A number of outer-rise regions exclusively exhibit normal-faulting seismic activity, an observation that is commonly attributed to an elevated level of in-plane tension induced by the plate-driving slab-pull force that allegedly precludes, or, at least, substantially diminishes, the development of compressional stress (Christensen & Ruff 1988; Dmowska et al. 1988; Liu & McNally 1993). If it is simply assumed that compressional lithospheric failure, whether brittle or plastic, is a sufficient condition for thrust-faulting seismicity, it is necessary for the in-plane tension to be applied subsequent to flexure to completely eliminate compressional failure and thereby preclude the possibility of thrust-faulting outer-rise earthquakes (e.g. Mueller et al. 1996, Fig. 7). Although it may be possible to construct a scenario in which this condition is satisfied, we suggest that a more robust explanation for the complete absence of thrust-faulting outer-rise earthquakes along the Aleutian, Mariana and Sunda subduction zones is simply that bending-induced compressional failure is restricted to the plastic regime, and that substantial levels of in-plane compression do not occur seawards of these subduction zones.

Even when outer-rise regions that are exclusively associated with normal-faulting seismic activity are excluded from consideration, it remains apparent that thrust-faulting outer-rise earthquakes occur less frequently than normal-faulting outer-rise earthquakes. We attribute this observation, for which the plate-bending interpretation offers no direct explanation, to our belief that only brittle failure is potentially seismogenic. Thrust-faulting outer-rise earthquakes therefore require an elevated level of in-plane compression, which, we suggest, is the exception, rather than the norm, for most outer-rise regions. Outer-rise-type plate bending can neither generate nor supplement brittle compressional lithospheric failure.

Even if it is assumed that bending-induced compression within the lower, plastic portion of the oceanic lithosphere is potentially seismogenic, appending an ad hoc element onto the plate-bending model so that it becomes consistent with the predominance of normal-faulting outer-rise earthquakes does not account for the observation that thrust-faulting outer-rise events generally do not occur within close lateral proximity to their normal-faulting counterparts. For example, a close examination of the outer-rise segments of the Middle America, Chile and Peru subduction zones that exhibit thrust-faulting activity reveals that this activity does not occur within close proximity to normal-faulting earthquakes (Figs 5a–c). The single thrust-faulting outer-rise earthquake known to have occurred within the Alaska–Aleutian subduction complex (Jaume & Estabrook 1992) was located within a region conspicuously devoid of normal-faulting seismic activity (Fig. 4). The spatial distribution of outer-rise seismicity clearly suggests that conditions favourable to the occurrence of thrust-faulting outer-rise earthquakes tend to preclude the occurrence of normal-faulting outer-rise earthquakes, and vice versa. It is therefore reasonable to conclude that these two types of outer-rise events reflect substantially different states of stress.

We suggest that isolated examples of proximal thrust- and normal-faulting outer-rise earthquakes reflect either a mis-classification of seismic activity or, perhaps, complex lithospheric deformation that does not occur solely in response to plate bending (e.g. that which may involve tearing or twisting of subducting lithosphere). Approximately one-third of the 'outer-rise earthquakes' catalogued by Christensen & Ruff (1988) were located landwards of the trench axis, where it is difficult to distinguish earthquakes confined to the subducting plate from those that occur within the overriding plate or along the interface between the subducting and overriding plates. Furthermore, even those 'landward events' that can be verified to have occurred within the subducting plate may reflect localized tectonic processes associated with the inter-plate environment, such as the dissection of a subducting seamount (Coulbourn, Hill & Bergersen 1989; Cloos 1992).
Events of this nature should be excluded from consideration when testing models of outer-rise seismicity. Outer-rise seismic activity within the Solomon Islands, as catalogued by Christensen & Ruff (1988), is illustrated in Fig. 5(d). Although it appears as if thrust- and normal-faulting 'outer-rise earthquakes' occurred within the immediate proximity of one another (Fig. 5d), both were actually located landwards of the trench axis (e.g. Christensen & Ruff 1988, Fig. 4). It is therefore conceivable, for example, that the thrust-faulting event may have represented a minor interplate slip event and/or the normal-faulting event may have occurred within the overriding plate. Although several of the Kurile Islands 'outer-rise earthquakes' catalogued by Christensen & Ruff 1988 indicate the occurrence of both thrust- and normal-faulting focal mechanisms within relatively close proximity, if those earthquakes that occurred landwards of the trench axis (Fig. 6, also see Christensen & Ruff 1988, Fig. 11) are eliminated from consideration, the remaining events indicate that the two mechanisms are spatially segregated.

It should be emphasized that, even if all of the 'landward events' are unconditionally accepted as outer-rise earthquakes, a pronounced tendency for the lateral segregation of thrust- and normal-faulting events remains evident. If all questionable 'outer-rise earthquakes' (i.e. those located landwards of the trench axis) are eliminated from consideration, the only remaining example of proximal thrust- and normal-faulting outer-rise earthquakes is a single pair of events located within the northern portion of the New Hebrides subduction complex (Christensen & Ruff 1988, Fig. 5). These events were located directly within the collisional zone of the East Rennel Island Ridge and the New Hebrides subduction zone, which suggests that one or both of the events may reflect complex lithospheric deformation that is not associated with typical outer-rise processes. In addition, the trench axis is often extremely poorly delineated where large bathymetric features are being subducted (e.g. Collot, Daniel & Burne 1985), suggesting that the classification of these events as outer-rise earthquakes may be questionable. This latter possibility is reinforced by the observation that the normal-faulting event in question, which occurred in 1964, is one of the 'oldest' reported by Christensen & Ruff (1988), suggesting that the location of this event is less reliably constrained than the majority of the events catalogued.

The sole example of a mixture of several thrust- and normal-faulting outer-rise earthquakes is located near the northern termination of the Tonga subduction zone (Fig. 7). Although these events may reflect a complex stress field associated with the plate tearing that is necessary to simultaneously accommodate subduction to the south and continued seafloor spreading to the north (Christensen & Ruff 1988), it is also possible that the classification of the normal-faulting events as outer-rise earthquakes is erroneous because all are located landwards of the trench axis.

2.3.2 Depth distribution

Although depth distributions of outer-rise earthquakes are commonly cited in support of the plate-bending interpretation.
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260° 265° 270°

280° 285° 290°

Middle America

Chile

Peru

Solomon Islands

Figure 5. Outer-rise earthquakes in Middle America, Chile, Peru, and the Solomon Islands. Open symbols denote normal-faulting events and solid symbols denote thrust-faulting events. Events located seawards of the trench axis, which, provided that the locations are reliable, are easily identified as outer-rise earthquakes, are represented by circles. ‘Outer-rise earthquakes’ located landwards of the trench axis, which potentially represent activity that is located within the overriding plate or associated with the interplate interface, are represented by squares. Routine classification of the latter as outer-rise earthquakes should be regarded as questionable.


Chapple & Forsth (1979) and Christensen & Ruff (1988) concluded that thrust-faulting outer-rise earthquakes occur systematically deeper than their normal-faulting counterparts, as predicted by the plate-bending interpretation. In more than half of the thrust-faulting events for which the depth was carefully determined, Christensen & Ruff (1988, Fig. 13) estimated the depth range of the rupture process. With a single exception, these estimates indicate that the thrust-faulting ruptures propagated to within at least 10 km of the seafloor, and that several are likely to have reached the seafloor, contradicting the bending interpretation. Shallow thrusting is also consistent with seismic refraction experiments immediately seawards of the Peru Trench, which indicate that the crustal structure is disrupted by deeply penetrating imbricate thrusts near the epicentral region of thrust-faulting outer-rise activity (Hussong, Odegard & Wipperman 1975; Prince & Kulm 1975; Hussong et al. 1976). Independent of the rheological difficulties discussed in Section 2.2, unless these earthquakes occurred within remarkably thin oceanic lithosphere (a possibility that is clearly precluded by the inferred rupture depth ranges), bending-induced compressional lithospheric failure will not extend upwards to within 10 km of the seafloor (e.g. Mueller et al. 1996, Fig. 3a).

Liu & McNally (1993) also attributed thrust-faulting outer-rise earthquakes to bending-induced compression within the lower portion of the oceanic lithosphere. Utilizing an elastic-plate model to determine the stress distribution that results from a specified combination of bending and in-plane force, they attempted to use earthquake source depths to determine the relative contribution of each. This approach, previously adopted by Chapple & Forsyth (1979) and Ward (1983, 1984), is founded upon the assumption that a transition from thrust- to normal-faulting earthquake focal mechanisms is sufficient to constrain the location of the neutral surface (i.e. the depth at which the tectonic stress is zero), which separates the tensional and compressional tectonic stress regimes. Because thrust- and normal-faulting outer-rise earthquakes do not
occur within close proximity to one another, this procedure typically requires that earthquakes distributed along 500 to 600 km of an outer-rise complex be projected onto a single 'representative' cross-section. Consequently, this approach implicitly assumes that variations in the relative contributions of flexure and in-plane force are negligible for comparable distances along strike of the trench axis (or, equivalently, that the depth of the neutral surface is relatively constant).

Although not commented upon by the authors, a peculiar feature of the source depth determinations of Liu & McNally (1993) is a pronounced tendency for both thrust- and normal-faulting events to cluster near the depth of the neutral surface, as predicted by their elastic-plate model. This implies, paradoxically, that the seismic activity is concentrated where the predicted tectonic stress level is minimal and the predicted lithospheric strength is near the maximum value. We suggest that this counter-intuitive implication is an artefact of projecting widely distributed outer-rise events, reflecting significantly different tectonic stress profiles, onto a single cross-section.

Both Christensen & Ruff (1988) and Liu & McNally (1993) concluded that elevated levels of in-plane compression contributed to the occurrence of thrust-faulting outer-rise earthquakes. As demonstrated by Mueller et al. (1996, Figs 3a and 6b), however, outer-rise-type plate bending invariably reduces the likelihood and/or extent of brittle compressional failure. Although we concur that high levels of in-plane compression are essential to the occurrence of thrust-faulting outer-rise seismicity, we reject the notion that a combination of bending-induced compression and in-plane compression may act to mutually reinforce the likelihood of thrust-faulting activity. If outer-rise seismicity is exclusively associated with a brittle lithospheric rheology, the ostensibly intuitive assumption that downward plate bending and in-plane compression may act in concert to produce thrust-faulting earthquakes (e.g. Ward 1983, 1984; Christensen & Ruff 1988; Dmowska & Lovison 1988; Dmowska et al. 1988; Liu & McNally 1993) must be discarded. For this reason, we suggest that invoking elevated levels of in-plane compression in an effort to account for thrust-faulting outer-rise earthquakes should not be regarded merely as a modification of the plate bending interpretation (e.g. Christensen & Ruff 1988; Liu & McNally 1993), but,
that the most powerful earthquakes within a specified region are most likely to nucleate at depths that correspond to the greatest levels of tectonic stress. Because the tectonic stress associated with in-plane compression increases with depth until the elastic core is encountered (e.g. Mueller et al. 1996, Figs 3b and 8), this suggests that a tendency may exist for teleseismically identifiable (i.e. the most powerful) thrust-faulting outer-rise earthquakes to be relatively deep. In Section 4.2, we propose a mechanism for inducing elevated levels of in-plane compression within outer-rise oceanic lithosphere.

3 OUTER-RISE DYNAMICS

In this section, we evaluate the influence of plate dynamics on lithospheric stress distributions within the outer-rise complex. Periods of enhanced normal-faulting activity within the outer-rise complex are sometimes observed to follow powerful subduction earthquakes (Stauder 1968; Abe 1972; Spence 1977, 1987; Christensen & Ruff 1983, 1988; Lay et al. 1989; Beck & Christensen 1991; Boyd, Engdahl & Spence 1995). Christensen & Ruff (1988) estimate that approximately 93 per cent of the normal-faulting outer-rise events that occur seawards of strongly coupled subduction interfaces follow gap-filling subduction earthquakes within less than 30 years. This increased level of outer-rise seismicity is believed to result from a 'tensional pulse' triggered by sudden slip at the trench (i.e. extension of the subducting plate constitutes an abrupt 'jerk' on this plate). This pulse, which essentially represents an in-plane-force adjustment, diffuses seawards at a rate governed by asthenospheric viscoelastic relaxation (Elsasser 1969; Melosh 1976; Spence 1977). Christensen & Ruff (1983, 1988) and Dmowska & Lovison (1988) proposed that in-plane-force perturbations of this nature are responsible for temporal variations in the occurrence of thrust- and normal-faulting outer-rise earthquakes. In this model, in-plane compression progressively accumulates between subduction earthquakes (i.e. during the interseismic period), triggering thrust-faulting outer-rise earthquakes shortly before the occurrence of a subduction earthquake. Normal-faulting outer-rise earthquakes are induced by the plate extension (i.e. in-plane tension) associated with the subduction earthquake. Although Christensen & Ruff (1988) suggested that relatively minor in-plane-force adjustments are sufficient, Dmowska & Lovison (1988) apparently envisioned much more substantial adjustments, describing the neutral surface as 'very shallow' prior to a subduction earthquake and 'rather deep' afterwards.

3.1 Outer-rise in-plane-force perturbations

We now examine the possibility that in-plane-force perturbations associated with underthrusting subduction earthquakes may induce a transition from thrust- to normal-faulting seismic activity within the outer rise. Subject to the conservative constraint that only brittle lithospheric failure is potentially seismogenic, such a transition would require that the resulting stress fluctuations be of sufficient magnitude to traverse the width of the brittle portion of the lithospheric yield envelope (e.g. Fig. 2). Using the representative yield envelope for oceanic lithosphere adopted by Mueller et al. (1996), the necessary stress perturbations at depths of 5 and 10 km are 320 and 595 MPa, respectively. Correspondingly larger perturbations are necessary at greater depths. Although lithospheric yield

Figure 7. Outer-rise earthquakes in the Tonga–Kermadec region. See Fig. 5 for symbol definitions.

rather, as an acknowledgment that the simple bending interpretation is untenable.

Although observed source-depth distributions are inconsistent with the plate bending interpretation of thrust-faulting outer-rise earthquakes, it does seem likely that these earthquakes are indeed characterized by a greater average depth than their normal-faulting counterparts. We offer a simple explanation for this observation. The plate-bending model, which represents a highly plausible explanation for normal-faulting outer-rise events, implies that these events are mechanically restricted to relatively shallow depths (e.g. Mueller et al. 1996, Fig. 3a). Consequently, any model of thrust-faulting outer-rise earthquakes that implies a less restrictive range of source depths will effectively predict that thrust-faulting activity will exhibit a greater average depth. Sibson (1982) concluded
envelope widths approach zero at the seafloor (e.g. Fig. 2), minor fluctuations in ambient tectonic stress are unlikely to promote the alleged transition in faulting mechanism for two reasons.

(1) Yield envelope construction assumes that optimally oriented faults are available for any slip direction (see Mueller et al. 1996). In reality, faults that are favourably oriented for thrust- and normal-faulting brittle slip are unlikely to coexist in close proximity within oceanic lithosphere, so that minor shifts in the ambient stress will not induce a transition from compressional brittle failure to tensile brittle failure, or vice versa.

(2) Even if such a transition were to occur, any faulting associated with minor stress fluctuations would be restricted to extremely shallow depths (e.g. tens of metres) and therefore severely limited in rupture extent. It is highly unlikely that such events would be teleseismically detectable.

In-plane-force perturbations induced by subduction earthquakes are governed by the amount of slip that occurs during the earthquake, and the first-order characteristics of this relationship may be quantified with a linear model of lithospheric stress diffusion (Elsasser 1969; Spence 1977). Predictions obtained on the basis of more elaborate, non-linear diffusion models (Melosh 1976) differ primarily in the timing of stress redistribution, and the maximum magnitude at a specific location is not significantly affected. A coseismic displacement, $u_0$, that occurs at time $t = 0$ induces a seaward displacement pulse described by (Elsasser 1969; Melosh 1976)

$$u(x, t) = u_0 \text{erfc}(x/\sqrt{4\kappa t}),$$

with $\kappa = Eh_1h_2/\eta$, where $E$ is Young's modulus, $h_1$ is the elastic-plate thickness, $h_2$ is the asthenospheric thickness, $\eta$ is the asthenospheric viscosity, and $x$ is measured relative to the assumed point of initial displacement. In-plane-force adjustment is determined by

$$F(x, t) = h_1 \sigma(z, t) = h_1E \frac{\partial u_0(x, t)}{\partial x} = \frac{-h_1E u_0}{\sqrt{\pi \kappa t}} \exp(-x^2/4\kappa t).$$

(Note that in-plane force is defined as force per unit length parallel to the trench axis and therefore has units of N m$^{-1}$.)

Although the 1960 Chilean subduction earthquake ($M_w 9.5$) may have involved as much as 25 m of slip (Stein et al. 1986), the amount of slip associated with most subduction earthquakes typically ranges from 2 to 10 m (Beck & Ruff 1984; Christensen & Ruff 1986; Mendoza & Hartzell 1989; Beck & Christensen 1991; Mendoza 1993). Adopting 10 m as a representative value for $u_0$, $7 \times 10^{18}$ Pa s for $\eta$ (Rydelek & Sacks 1988), 65 GPa for $E$, 40 km for $h_1$, and 75 km for $h_2$, in-plane-force perturbations at various times following a subduction earthquake are presented in Fig. 8.

Outer-rise in-plane-force perturbations predicted at distances of 20 and 150 km from the up-dip limit of coseismic slip (the region that is likely to encompass most of the outer-rise complex) correspond to average stress fluctuations of approximately 15 and 2.5 MPa (150 and 25 bars), respectively. Because this range includes stress-drop estimates of several subduction earthquakes (e.g. Houston & Kanamori 1986; Choy & Dewey 1988; Mendoza 1993), our analysis provides quantitative support for the suggestion by Seno & Honda (1990) that outer-rise stress perturbations induced by subduction earthquakes are of the same order as the stress drop of the earthquake. We emphasize that the result obtained above

![Figure 8](https://academic.oup.com/gji/article-abstract/125/1/54/705032)

Figure 8. In-plane-force perturbations induced by the plate extension associated with a subduction earthquake. Subscripts refer to the number of days following the earthquake. Estimates are derived from a simple model of linear stress diffusion and are plotted as a function of distance from an idealized point of slip. The exceptionally large values near the origin are an artefact of the unrealistic assumption that all of the coseismic slip is concentrated at a single point.

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represents an upper limit on in-plane-force perturbations only; in no manner does this result represent a limitation on the absolute level of in-plane force.

Because the stress perturbations predicted throughout the outer-rise complex are substantially less than those necessary to induce a transition between thrust- and normal-faulting intraplate earthquakes, our analysis predicts one of two mutually exclusive possibilities:

1. If the state of stress within an outer-rise segment is characterized by compressional brittle failure, thrust-faulting earthquakes may precede subduction earthquakes (in response to a slight increase in the level of in-plane compression), but normal-faulting earthquakes are unlikely to follow such earthquakes;

2. If the state of stress within an outer-rise segment is characterized by compressional or tensional brittle failure, normal-faulting earthquakes may follow subduction earthquakes (in response to a slight increase in the level of in-plane tension), but thrust-faulting earthquakes are unlikely to precede such earthquakes.

In case (1), elastic unloading within the region of compressional brittle failure is induced by the plate extension (i.e. in-plane tension) associated with the subduction earthquake. This shifts the stress distribution slightly away from the yield envelope boundary, precluding the possibility of failure until the progressive accumulation of in-plane compression during the interseismic period gradually shifts it back again. In case (2), elastic unloading within the region of tensional brittle failure is gradually induced by the progressive accumulation of in-plane compression during the interseismic period. This also shifts the stress distribution slightly away from the yield envelope boundary (except, in this case, it is away from the tensional side), precluding the possibility of failure until the occurrence of a plate-extending subduction earthquake suddenly shifts it back again.

For these reasons, our model of outer-rise seismicity implies that an absence of large outer-rise earthquakes is likely to either precede or follow a subduction earthquake, although we caution that this model may not apply in cases involving extremely complex lithospheric deformation (e.g. tearing and/or twisting). Whether the predicted outer-rise inactivity preceeds or follows a subduction earthquake depends upon the state of stress within the affected outer-rise segment (i.e. whether it is characterized by compressional or tensional brittle failure). Christensen & Ruff (1988) cited two examples in support of their contention that a transition may occur in which the outer-rise region is characterized by thrust-faulting activity prior to a subduction earthquake and normal-faulting activity following a subduction earthquake. One of the proposed transitional sequences occurred within the Kurile Islands subduction zone and involves ‘outer-rise events’ that were located landwards of the trench axis. As illustrated in Fig. 6, the elimination of landward events, which cannot reliably be assumed to represent outer-rise earthquakes (e.g. Section 2.3.1), reveals a distinct time-independent spatial segregation between thrust- and normal-faulting outer-rise earthquakes in the Kurile Islands. The remaining example of a transition from thrust- to normal-faulting outer-rise seismicity offered by Christensen & Ruff (1988) involved the only thrust-faulting outer-rise earthquake that has been documented within the New Hebrides region. As discussed in Section 2.3.1, a number of considerations render their interpretation questionable. If the state of stress within the outer-rise complex does tend to conform to a cycle in which the potential for thrust-faulting seismic activity exists prior to subduction earthquakes and the potential for normal-faulting seismic activity exists following subduction earthquakes, one would anticipate that an observable transition from thrust- to normal-faulting outer-rise earthquakes would not prove so elusive.

4 ALTERNATIVE MODELS OF THRUST-FAULTING OUTER-RISE EARTHQUAKES

The rheological difficulties associated with the plate bending model of thrust-faulting outer-rise earthquakes, combined with the failure of this model to account for the observed spatial and temporal distributions of outer-rise seismic activity, dictate that alternative interpretations of these earthquakes must be considered.

4.1 Alternative models

4.1.1 Thermoeelastic stress

Due to depth-dependent differences in cooling rate, deeper layers of oceanic lithosphere have a tendency to contract more rapidly than shallow layers. Because the various layers are welded together, however, they are prevented from contracting independently of one another and this constraint results in the development of thermally induced stresses within the cooling plate. If the lithosphere is allowed to contract freely, the thermally induced stress distribution is characterized by shallow compression and deeper tension (Wessel 1992). The observed predominance of thrust-faulting focal mechanisms within thermally mature, non-outter-rise, intraplate regions (Wiens & Stein 1984) suggests that some contraction of the lithosphere does occur and the potential for thermally induced thrust-faulting outer-rise earthquakes should therefore be considered.

Fig. 9(a) illustrates a representative example of a thermoelastic tectonic stress distribution (following Wessel 1992) for 100 Ma oceanic lithosphere. Because the brittle compressional failure is confined to relatively shallow depths, thermally induced stress cannot represent a comprehensive model for thrust-faulting outer-rise earthquakes, which often exhibit source depths that exceed 10 km. Moreover, the accumulation of thermoelastic stress occurs prior to lithospheric migration into the outer-rise complex and all traces of brittle compressional failure are therefore eliminated by elastic unloading during the plate bending that follows, even if relatively small values of plate curvature are involved (Fig. 9b). In fact, typical values of plate curvature (Fig. 9c) result in tectonic stress distributions that differ only marginally from those that result from the bending of an initially stress-free plate (e.g. compare Fig. 9c with Fig. 3a of Mueller et al. 1996). The only ‘memory’ of the initial, thermally induced, stress distribution is a slight degree of non-linearity within the elastic core.

4.1.2 Lithospheric unbending

Stress distributions presented by Mueller et al. (1996, Fig. 4) indicate that compressional brittle failure is a direct
These stresses, which arise in response to differences in depth-dependent cooling rates, result in compressional brittle failure at shallow depths. (b) Because of elastic unloading, even minimal amounts of outer-rise-type bending (e.g. $2 \times 10^{-7} \text{ m}^{-1}$) eliminate all traces of brittle compressional failure. (c) More typical values of plate curvature (in this case, $4 \times 10^{-7} \text{ m}^{-1}$) result in stress distributions that are only marginally different from that associated with bending alone. The only 'memory' of thermally induced stress is a slight degree of non-linearity within the elastic core.

Figure 9. (a) Thermally induced stress distribution for 100 Ma oceanic lithosphere (after Wessel 1992). These stresses, which arise in response to differences in depth-dependent cooling rates, result in compressional brittle failure at shallow depths. (b) Because of elastic unloading, even minimal amounts of outer-rise-type bending (e.g. $2 \times 10^{-7} \text{ m}^{-1}$) eliminate all traces of brittle compressional failure. (c) More typical values of plate curvature (in this case, $4 \times 10^{-7} \text{ m}^{-1}$) result in stress distributions that are only marginally different from that associated with bending alone. The only 'memory' of thermally induced stress is a slight degree of non-linearity within the elastic core.

Consequence of a reduction in plate curvature. Reversal of the mode of failure (i.e. tensile to compressional, or vice versa) near upper and lower plate margins in response to the 'unbending' of an inelastic plate is a routinely documented phenomenon in plasticity engineering (Johnson & Mellor 1962; Drucker 1967). In the case of oceanic lithosphere, it is theoretically possible that at least some degree of compressional brittle failure will occur in response to even minor amounts of unbending because the width of the idealized lithospheric yield envelope is effectively zero at the sea-floor (e.g. Mueller et al. 1996, Fig. 1).

The notion that lithospheric unbending within the outer trench wall may influence seismicity patterns near the trench axis was initially proposed by Bodine et al. (1981). It is generally acknowledged that at least some degree of unbending occurs within this region (e.g. McAdoo, Caldwell & Turcotte 1978; Turcotte, McAdoo & Caldwell 1978; Bodine & Watts 1979; Chapple & Forsyth 1979; Bodine et al. 1981), and Chapple & Forsyth (1979) reported that seismic reflection profiles within outer trench walls sometimes reveal a transition from normal-faulting activity to thrust-faulting activity a short distance seawards of the trench axis. In addition, many of the thrust-faulting ‘outer-rise earthquakes’ catalogued by Christensen & Ruff (1988) were actually located within the outer trench wall.

Fig. 10 depicts the maximum depth extent of brittle compressional failure that is associated with the unbending of 50 and 100 Ma oceanic lithosphere. Even in the case of complete unbending from a relatively extreme maximum curvature of $1 \times 10^{-6} \text{ m}^{-1}$, brittle compressional failure does not extend to greater than 14 km depth. Because some thrust-faulting outer-rise earthquakes that have been studied in detail appear to have ruptured to greater depths (Chapple & Forsyth 1979; Ward 1983; Christensen & Ruff 1985, 1988; Honda et al. 1990; Tichelaar et al. 1992; Liu & McNally 1993), lithospheric unbending cannot represent a comprehensive explanation for these events. The possibility that lithospheric unbending is responsible for some thrust-faulting outer-rise earthquakes, however, cannot be ruled out.

4.1.3 In-plane compression

Elevated levels of in-plane compression that accumulate subsequent to outer-rise-type plate bending represent the simplest consequence of a reduction in plate curvature. Reversal of the mode of failure (i.e. tensional to compressional, or vice versa) near upper and lower plate margins in response to the 'unbending' of an inelastic plate is a routinely documented phenomenon in plasticity engineering (Johnson & Mellor 1962; Drucker 1967). In the case of oceanic lithosphere, it is theoretically possible that at least some degree of compressional brittle failure will occur in response to even minor amounts of unbending because the width of the idealized lithospheric yield envelope is effectively zero at the sea-floor (e.g. Mueller et al. 1996, Fig. 1).

The notion that lithospheric unbending within the outer trench wall may influence seismicity patterns near the trench axis was initially proposed by Bodine et al. (1981). It is generally acknowledged that at least some degree of unbending

Figure 10. Maximum depth extent of compressional brittle failure that may result from lithospheric unbending within the outer trench wall. All curves assume zero in-plane force. (a) 100 Ma oceanic lithosphere. (b) 50 Ma oceanic lithosphere. The plate curvature at the onset of unbending is the curvature value that corresponds to zero depth. As the curve is followed to the left, decreasing values of curvature correspond to the 'unbent' value. The plate has resumed its original (i.e. pre-outer-rise bending) configuration at zero curvature.

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manner in which to promote relatively deep brittle compressional failure of oceanic lithosphere within the outer-rise complex (e.g. Mueller et al. 1996, Figs 6a and 8). The most familiar source of in-plane compression is the ridge-push force, which is induced by the elevation of young oceanic lithosphere with respect to the abyssal plain (Parsons & Richter 1980). Because the ridge-push force is invariably small with respect to the net compressional strength of oceanic lithosphere, however, the depth to which the resulting brittle compressional failure may extend is severely limited. For example, a ridge-push force within 100 Ma oceanic lithosphere would induce such failure to a depth of less than 2 km (Fig. 11a). Moreover, because the ridge-push force accumulates prior to the migration of a lithospheric segment into the outer-rise complex, elastic unloading associated with outer-rise bending eliminates all traces of brittle compressional failure (Fig. 11b).

The development of brittle compressional failure at depths that correspond to the vertical range of rupture that has been observed to be associated with thrust-faulting outer-rise earthquakes requires a level of in-plane compression that exceeds maximum ridge-push values by nearly an order of magnitude. A mechanism for generating substantially elevated levels of in-plane compression is proposed in the following section; at this point, we simply examine the consequences for outer-rise seismicity. Provided that the level of in-plane compression does not equal the net compressional lithospheric strength, the maximum nucleation and/or propagation depth of thrust-faulting earthquakes will be limited by the barrier-like elastic core (not the idealized brittle-plastic transition) (e.g. Mueller et al. 1996, Figs 3b and 8c). Given uncertainties in oceanic lithospheric yield envelopes (e.g. Fig. 2), this depth may approach 50 km as the applied in-plane compression approaches the upper limit represented by the net compressional lithospheric strength.

As discussed in the following section, seaward 'jumps' of subduction boundaries indicate that outer-rise in-plane compression does occasionally attain the net compressional strength of oceanic lithosphere. In this case, the elastic core is eliminated and thrust-faulting ruptures may propagate below the predicted depth of the idealized brittle-plastic transition for two reasons.

1. As discussed by Mueller et al. (1996, Section 3.2), the transition from brittle to plastic behaviour is not abrupt and is therefore unlikely to constitute a sharply defined barrier.

2. A strain-rate-induced coseismic depression of the brittle-plastic transition may occur (Mueller et al. 1996, Fig. 2a; Section 2.2.2). Note that, because a coseismic depression of the transitional boundary must be triggered by an earthquake, such a mechanism cannot promote the nucleation of subtransitional earthquakes, but, rather, can only facilitate the downward propagation of ruptures below the transitional depth.

In contrast to the brittle tensional failure induced by outer-rise-type bending, brittle compressional failure induced by in-plane compression is not restricted to a relatively shallow depth range, provided that a sufficiently elevated level of in-plane compression is available. This suggests that, if thrust-faulting outer-rise earthquakes are associated with substantial levels of in-plane compression, these events should be characterized by a greater average depth than their normal-faulting counterparts. For this reason, the tendency for thrust-faulting outer-rise events to be deeper than normal-faulting outer-rise earthquakes should not be uncritically accepted as evidence that the bending interpretation is valid for both types of outer-rise earthquakes (e.g. Chapple & Forsyth 1979; Ward 1983, 1984; Christensen & Ruff 1988; Seno & Honda 1988; Honda et al. 1990; Tichelaar et al. 1992; Liu & McNally 1993).

Finally, the sole region (of which we are aware) in which seismic refraction methods have been utilized to determine crustal structure proximal to thrust-faulting outer-rise seismic activity strongly supports our contention that this activity is associated with an elevated level of in-plane compression. Seismic refraction profiles indicate deeply penetrating imbricate thrusts, suggesting considerable levels of in-plane compression, immediately seawards of the Peru Trench (Hussong et al. 1975; Prince & Kulm 1975; Hussong et al. 1976) within the epicentral region of several thrust-faulting outer-rise earthquakes (Fig. 5c; Christensen & Ruff 1988, Fig. 8).

### 4.2 The stress concentrator model

We propose that the elevated levels of in-plane compression necessary for the occurrence of thrust-faulting outer-rise earthquakes are associated with stress concentrations within the subducting plate that are induced by localized resistance to the regionally distributed forces responsible for plate convergence. This mechanism is a generalization of a model presented by Christensen & Ruff (1988). The requisite conditions for a...
stress concentrator are simply that the driving forces are broadly distributed and the resisting forces are relatively localized. In contrast to isolated patches of strong interplate coupling, which may be relatively limited in spatial extent, the slab-pull and ridge-push forces responsible for plate convergence are regionally distributed and the conditions necessary for the development of stress concentrations are therefore satisfied. Qualitatively, the pattern of stress concentrations within the subducting plate is determined solely by the relative direction of plate convergence. For this reason, elevated levels of in-plane compression seawards of an impeded trench segment, combined with elevated levels of in-plane tension within the subducting slab downdip of such a segment, would be anticipated regardless of whether oceanic plates are predominantly pushed or pulled into the trench.

4.2.1 Trench congestion and subduction-zone asperities

One manner in which stress concentrations may be induced within subducting oceanic lithosphere involves the attempted subduction of substantial amounts of relatively buoyant material, such as an isostatically compensated seamount chain, oceanic plateau or island-arc massif. The resulting 'trench congestion' represents resistance to plate convergence that is restricted to the affected trench segment, satisfying the requisite conditions for a stress concentrator and resulting in elevated levels of in-plane compression within the outer-rise complex (e.g. Kelleher & McCann 1976; Mueller & Phillips 1991). A number of the thrust-faulting outer-rise earthquakes catalogued by Christensen & Ruff (1988) were located directly seawards of trench segments characterized by the subduction of pronounced bathymetric features. Examples include two Peruvian events located near the Grijalva Ridge, two Chilean events located near the Juan Fernandez Ridge, and a Tongan event located near the Louisville Ridge. The single documented examples of thrust-faulting outer-rise earthquakes within the New Hebrides and Alaska–Aleutia subduction complexes were located near the East Rennel Island Ridge and within the Alaska Seamount region, respectively (Christensen & Lay 1988; Jaume & Estabrook 1992). In addition, it is, perhaps, significant that thrust-faulting outer-rise events within the Solomon Islands are restricted to the western end of the complex, where the trench has been congested by the attempted subduction of the New Guinea margin.

Trench congestion associated with the attempted subduction of the Izu–Bonin Ridge (an island-arc massif) has apparently resulted in a level of in-plane compression sufficient to induce whole-lithospheric failure within the subducting Philippine Sea plate (Chamot-Rooke & Le Pichon 1989; Lallemant et al. 1989; Taira, Tokuyama & Soh 1989). Additional examples in which trench congestion has resulted in seaward 'jumps' of subduction boundaries, indicating compression failure throughout the entire thickness of the oceanic lithosphere, are documented in Collet et al. (1985), Mueller & Phillips (1991) and Scholl et al. (1992). Severe trench congestion within the Himalayan tectonic zone, combined with continued subduction along the adjacent Sunda Arc, has resulted in extreme levels of in-plane compression within the equatorial Indian Ocean (Cloetingh & Wortel 1986; Govers et al. 1992), which geophysical observations indicate is sufficient to induce lithospheric buckling (McAdoo & Sandwell 1985; Zuber 1987) and, possibly, the formation of a new subduction zone (Weissel, Anderson & Geller 1980; Wiens et al. 1985). Collectively, observations such as these substantiate our contention that trench congestion may result in extreme levels of in-plane compression.

Many of the thrust-faulting outer-rise earthquakes catalogued by Christensen & Ruff (1988) are not obviously associated with the subduction of bathymetric irregularities. Stress concentrations may also be induced by patches of strong interplate coupling, referred to as subduction-zone asperities, that impede plate convergence and promote the development of seismic gaps. The coseismic slip associated with an underthrusting subduction earthquake, which essentially represents an attempt by an impeded segment of a subducting plate to 'catch up' with adjacent, unimpeded segments, is triggered by the failure of an impeding subduction-zone asperity (Christensen & Ruff 1986; Schwartz, Dewey & Lay 1989). Seismic analysis of subduction earthquakes reveals that the associated slip is restricted to the immediate vicinity of the asperity and that adjacent portions of the subduction interface slip aseismically during the period that the asperity remains locked (Beck & Ruff 1984; Houston & Engdahl 1989). These observations indicate that the resistance to plate convergence is localized directly at the asperity and the conditions for a stress concentrator are therefore satisfied. Christensen & Ruff (1988) conclusively demonstrated that the occurrence of thrust-faulting outer-rise activity is often correlated with the presence of interplate asperities.

Trench congestion that results from the attempted subduction of isostatically compensated features may be associated with the development of subduction-zone asperities (e.g. Christensen & Lay 1988; Cloos 1992). For this reason, the two processes of inducing stress concentrations that we have described are not necessarily unrelated. Finally, because stress concentrations will be restricted to the immediate vicinity of a subduction-zone asperity, the loading-order constraint described by Mueller et al. (1996), which requires that the in-plane compression occurs subsequent to outer-rise type bending, is likely to be satisfied.

4.2.2 Rupture of subduction-zone asperities

In addition to an elevated level of in-plane compression within the seaward portion of the subducting plate, the stress concentrator model also predicts that an elevated level of in-plane tension should exist within the portion of the subducting plate that is down-dip of the subduction-zone asperity. Because the seaward compression represents a pushing on the subducting plate that is directed toward the asperity and the down-dip tension represents a pulling on the plate that is directed away from the asperity, it is plausible to assume that these stress concentrations contribute to the rupture of the asperity.

The rupture of subduction-zone asperities has been previously attributed primarily to the progressive accumulation of down-dip tension associated with the plate-driving slab-pull force (McNally, Gonzalez-Ruiz & Stolte 1986; Spence 1987). The existence of down-dip intraslab tension is supported by the observation that subduction earthquakes are sometimes preceded by normal-faulting earthquakes within the subducting slab below the associated interplate asperity (McNally et al. 1986; Lay et al. 1988; Langer & Spence 1995). Because the qualitative pattern of stress concentrations (seaward compression and down-dip tension) reflects only the direction of
plate convergence, and is therefore entirely consistent with the common perception of the slab-pull force as the dominant plate driver, our suggestion that the rupture of subduction-zone asperities is facilitated by stress concentrations should be regarded as a modification of, rather than a repudiation of, the previous interpretation, which simply failed to recognize that the ambient plate-driving forces are effectively amplified in the immediate vicinity of an isolated interplate asperity. Some precursory, intermediate-depth, normal-faulting intraslab events are more readily accounted for on the basis of the stress concentrator model. For example, intraslab earthquakes of this nature have recently been observed down-dip of the interplate asperity that is presumably responsible for the Guerrero seismic gap of southern Mexico (Suárez et al. 1990), a region in which slab-pull-induced tension is likely to be severely diminished by the young age and subhorizontal geometry of the subducting plate.

The model that we propose does not predict that all subduction-zone asperities are associated with significant concentrations of stress. Such concentrations will be diminished considerably if the region of strong interplate coupling extends for a great distance along strike of the trench because the resistance to plate convergence is broadly distributed. (Note that, in regard to stress concentrations, a number of closely spaced smaller asperities will likely have an effect similar to a single, larger asperity because, in both cases, the resistance to plate convergence is not localized.) This offers a plausible explanation for the observation that the most powerful subduction earthquakes, which involve the rupture of asperities that extend along strike of the trench for the greatest distances (Ruff & Kanamori 1983; Beck & Ruff 1987; Ruff 1992), have never been observed to be preceded by thrust-faulting outer-rise activity (Lay et al. 1989). The stress concentrator model therefore implies that somewhat different mechanisms are responsible for the rupture of small and large subduction-zone asperities. The latter rupture directly in response to the progressive accumulation of slab-pull-induced tension (with minimal amplification), whereas rupture of the former is facilitated by the development of stress concentrations.

Because the slab-pull force induces in-plane tension down-dip of all subduction-zone asperities, regardless of size, our model is consistent with the observation of McNally et al. (1986) that intermediate-depth normal-faulting intraslab earthquakes may precede subduction earthquakes of any magnitude. Intraslab seismicity of this nature may directly reflect the existence of slab-pull-induced tension or represent a manifestation of stress concentrations. In contrast, the occurrence of thrust-faulting activity within the outer-rise complex requires the existence of stress concentrations, which may be significantly diminished in the case of large subduction-zone asperities.

5 CONCLUSIONS

On the basis of inelastic analysis of lithospheric stress distributions, we conclude that thrust- and normal-faulting outer-rise earthquakes represent fundamentally different states of stress within the oceanic lithosphere. Previous interpretations have attributed both types of outer-rise seismic activity to the same bending-dominated tectonic stress distribution. We have demonstrated that, if outer-rise seismicity is exclusively associated with a brittle rheology, the ostensibly intuitive notion that bending-induced compression within the lower portions of the oceanic lithosphere may promote thrust-faulting earthquakes is erroneous. This interpretation implies either earthquake generation in response to predominantly non-brittle deformation or extremely weak oceanic lithosphere, both of which are highly problematic. Our results indicate that normal-faulting outer-rise earthquakes are primarily a consequence of downward plate bending, whereas thrust-faulting outer-rise earthquakes are associated with elevated levels of in-plane compression.

In contrast to in-plane compression-dominated stress distributions, which are likely to occur only in response to specific tectonic situations, bending-dominated stress distributions probably represent the 'standard' outer-rise state of stress. Our interpretation therefore offers a plausible explanation for the observation that normal-faulting outer-rise earthquakes are more widely distributed than their thrust-faulting counterparts. Attributes both thrust- and normal-faulting outer-rise earthquakes to plate bending does not account for the predominance of the latter. Moreover, the simple bending model also implies, contrary to observation, that thrust- and normal-faulting outer-rise earthquakes should occur within relatively close proximity to one another, since both are allegedly generated by the same bending-dominated stress distribution. We attribute the observation that thrust-faulting outer-rise events are characterized by a greater average source depth than their normal-faulting counterparts, which is frequently cited in support of the simple bending model, to the mechanical constraint that bending-induced tensional failure is necessarily restricted to the uppermost oceanic lithosphere. In fact, the observation that some thrust-faulting outer-rise events have ruptured upwards nearly to the sea-floor is inconsistent with the simple bending interpretation.

We utilize analytical models of lithospheric stress diffusion to demonstrate that in-plane-force variations associated with the plate extension that accompanies powerful subduction earthquakes must be relatively small. This implies that, in the absence of extremely complex lithospheric deformation, subduction earthquakes may be preceded by thrust-faulting outer-rise earthquakes or followed by normal-faulting outer-rise earthquakes, but that both classes of outer-rise seismicity cannot be associated with the same subduction earthquake. Our results are therefore inconsistent with the suggestion of Christensen & Ruff (1988) that an outer-rise 'earthquake cycle' exists, in which this region is characterized by a transition from thrust-faulting activity prior to a subduction earthquake to normal-faulting activity following a subduction earthquake.

We attribute the elevated level of in-plane compression that we have inferred to be necessary for the occurrence of thrust-faulting outer-rise earthquakes to stress concentrations within the subducting plate that develop in response to either trench congestion or the presence of a subduction-zone asperity. Both trench congestion, which is characterized by the attempted subduction of substantial amounts of isotastically compensated (i.e. buoyant) material, and subduction-zone asperities, which represent patches of strong interplate coupling, may result in relatively localized resistance to the regionally distributed forces that promote plate convergence. These constitute conditions for a classic stress concentrator: broadly distributed driving forces, combined with relatively localized resistsitng forces. The qualitative pattern of stress concentrations within the subducting plate—elevated levels of in-plane compression
seaward of the impeded trench segment and elevated levels of in-plane tension down-dip of this segment—reflect only the direction of plate convergence and will exist regardless of whether the plate is predominantly pushed or pulled into the trench. Seaward jumps of congested subduction boundaries indicate that outer-rise in-plane compression does occasionally attain the net compressional strength of oceanic lithosphere.

Finally, the stress concentrator model offers a plausible explanation for the observation that the most powerful subduction earthquakes have never been preceded by thrust-faulting outer-rise activity (Lay et al. 1989). The most powerful subduction earthquakes generally involve the rupture of subduction-zone asperities that extend along strike of the trench axis for considerable distances (e.g. Ruff & Kanamori 1983; Beck & Ruff 1987). Whether continuous or consisting of several closely spaced smaller asperities, such asperities would be relatively inefficient at inducing significant levels of stress concentrations within a subducting plate because the resistance to plate convergence is broadly distributed.

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