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More than one way to stretch: a tectonic model for extension along the plume track of the Yellowstone hotspot and adjacent Basin and Range Province

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Abstract. The eastern Snake River Plain of southern Idaho poses a paradoxical problem because it is nearly aseismic and unfaulted although it appears to be actively extending in a SW-NE direction continuously with the adjacent block-faulted Basin and Range Province. The plain represents the 100-km-wide track of the Yellowstone hotspot during the last ~16-17 m.y., and its crust has been heavily intruded by mafic magma, some of which has erupted to the surface as extensive basalt flows. Outside the plain's distinct topographic boundaries is a transition zone 30-100 km wide that has variable expression of normal faulting and magmatic activity as compared with the surrounding Basin and Range Province. Many models for the evolution of the Snake River Plain have as an integral component the suggestion that the crust of the plain became strong enough through basaltic intrusion to resist extensional deformation. However, both the boundaries of the plain and its transition zone lack any evidence of zones of strike slip or other accommodation that would allow the plain to remain intact while the Basin and Range Province extended around it; instead, the plain is coupled to its surroundings and extending with them. We estimate strain rates for the northern Basin and Range Province from various lines of evidence and show that these strains would far exceed the elastic limit of any rocks coupled to the Basin and Range; thus, if the plain is extending along with its surroundings, as the geologic evidence indicates, it must be doing so by a nearly aseismic process. Evidence of the process is provided by volcanic rift zones, indicators of subsurface dikes, which trend across the plain perpendicular to its axis. We suggest that variable magmatic strain accommodation, by emplacement and inflation of dikes perpendicular to the least principal stress in the elastic crust, allows the crust of the plain to extend nearly aseismically. Dike injection releases accumulated elastic strain but generates only the small earthquakes associated with dike propagation. The rate of dike emplacement required to accommodate the estimated longitudinal strain rate of the plain is roughly a composite width of 10 m every 1000 years for the geologically youngest and most active part of the plain. The locus of most rapid intrusion and strain has migrated toward Yellowstone and is now in the northeastern 100-150 km of the plain. Reduced magmatic input in the transition zone of the plain causes the transitional expression of seismicity and faulting there.

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1. Introduction

A persistent problem in tectonics lies in understanding how strong variations in apparent surface strain are balanced, particularly when such variations occur across very abrupt transitions. In this paper we focus on the eastern Snake River Plain in southern Idaho (Figure 1), which we feel represents an end-member example of such an abrupt transition in strain accommodation. The eastern Snake River Plain forms a spectacular low topographic corridor across the actively extending northern Basin and Range Province (Figure 1). The plain is remarkable not only for its virtual lack of topographic relief when compared to the surrounding Basin and Range but also for its almost complete lack of contemporary and historical seismicity and lack of evidence for any persistent paleoseismicity (no normal faults with significant accumulated displacement). The eastern Snake River Plain marks the track left by the Yellowstone hotspot as the North American Plate moved southwest over it and is thinly covered (~1 km where drilled) by young basalt flows (most < 5 m.y. old) [e.g., *Luedke and Smith,* 1983; *Hackett and Smith,* 1992]. There is evidence, based on stratigraphic relations and improved dating of silicic volcanism, that despite its lack of earthquakes and block faults, the eastern Snake River Plain extends along with the surrounding Basin and Range Province [*Rodgers et al.*, 1990].

The lack of developed fault-block topography on the eastern Snake River Plain and low seismicity in the plain and in its transition zone indicate that the plain and local surroundings do not respond to the regional extensional stress field in the same manner as the Basin and Range Province. Alternate mechanisms for the development of the eastern Snake River Plain have been proposed by many authors. These fall more or

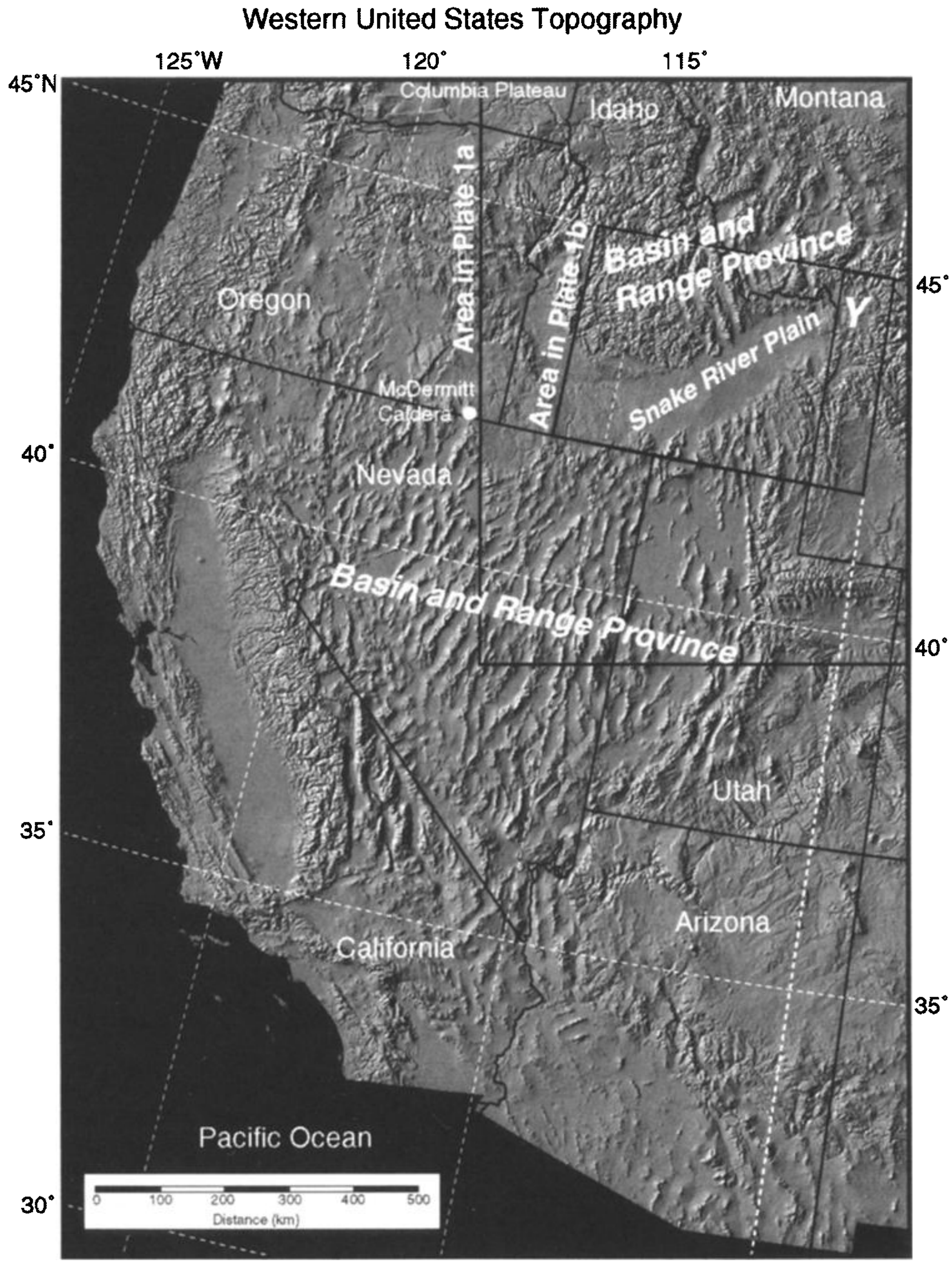

Figure 1. Topography of the Basin and Range Province [*Thelin and Pike*, 1991]. The low-relief Snake River Plain is one of the most distinctive topographic features of the province. Yellowstone is marked by the letter, "Y". Rectangles show the areas covered in Plates 1a and 1b.

less into four categories: (1) The eastern Snake River Plain is too weak to fail by faulting because of thermal input from the Yellowstone hotspot and creeps aseismically [e.g., *Furlong*, 1979; *Brott et al.*, 1981]. (2) The eastern Snake River Plain is too strong to fail by faulting because the midcrust was replaced by relatively strong basalt [e.g., *Anders et al.*, 1989; *Smith and Arabasz*, 1991]. (3) The eastern Snake River Plain and transition zone were weakened while the hotspot passed beneath it causing fast extension, and then subsequent cooling after the hotspot passed prevented further failure [*Anders and Sleep*, 1992]. (4) The eastern Snake River Plain and transitional zone extend by variable amounts of dike intrusion, limiting or preventing the formation of normal faults (this study).

The limited strength of continental crust imposes constraints on how much variation in strain rate and mode can exist. For example, if the northern Basin and Range Province has been extending at a constant rate while the eastern Snake

River Plain has not been extending, then unrealistically large differential stresses are predicted to build up in the eastern Snake River Plain crust, or accommodation zones such as strike slip faults are predicted along the boundaries of the plain. In this paper we subject the various models for the eastern Snake River Plain to the criterion that over the past 10 m.y. since the Yellowstone hotspot passed beneath the region, there has been regionally balanced extensional strain both in area and in depth across the eastern Snake River Plain and Basin and Range Provinces. We examine the topography, seismicity, gravity data, aeromagnetic data, the age and distribution of faults, fault-slip rates, the age and distribution of basaltic volcanism, strain rate indicators, and in situ stress indicators to develop a consistent strain-balanced model for the post-Yellowstone hotspot evolution of the eastern Snake River Plain.

2. Observational Data

While the most striking feature of the eastern Snake River Plain is the abrupt topographic transition from the basins and ranges north and south of the plain to the low-relief interior, many of the geologic and geophysical signals indicate that the province continues beyond its topographic boundaries into a transition zone surrounding it. This transition zone is highly variable in character and width.

2.1. Seismicity

The interior of the eastern Snake River Plain is virtually aseismic; the largest quakes recorded have magnitudes less than 1.5 [*Jackson et al.*, 1993]. Distributed outside the plain and its transition zone is some of the most active extensional faulting in the Basin and Range Province. Many authors have noted an apparent parabolic distribution of seismicity around the eastern Snake River Plain [e.g., *Myers and Hamilton*, 1964; *Smith and Sbar*, 1974] and that there is a seismically quiet rim around the eastern Snake River Plain, part of an "interior parabola" or "collapse shadow" [*Anders et al.*, 1989]. The distribution of seismicity around the eastern Snake River Plain is shown in Plate 1; a northerly trend of seismicity associated with the Wasatch front merges into activity at the Yellowstone Plateau, and a cluster of seismicity is distributed around the epicenter of the 1983 magnitude 7.3 Borah Peak earthquake north of the plain. In general, seismicity tapers off about 50-70 km away from the topographic edge of the eastern Snake River Plain.

2.2. Magmatism

During the past 16-17 m.y. the North American plate has moved southwest over the Yellowstone plume, leaving the Snake River Plain behind as its track [*Morgan*, 1972; *Armstrong et al.*, 1975; *Pierce and Morgan*, 1992]. The Yellowstone hotspot emerged with a burst of basaltic volcanism that formed the dike-fed Columbia River flood basalts and Oregon Plateau basalts to the northwest and the dike swarms of the northern Nevada rift to the southeast [*Zoback and Thompson*, 1978; *Pierce and Morgan*, 1992; *Zoback et al.*, 1994]; contemporaneous silicic volcanism was centered on the McDermitt caldera in northern Nevada. Magmatic activity on the Eastern Snake River Plain was initially characterized by pulses of silicic volcanism (each ~2-3 m.y. duration) progressing toward the present Yellowstone caldera. Extensive basaltic volcanism followed, covering the plain [e.g., *Luedke and Smith*, 1983]. Seismic refraction data indicate much larger volumes of intruded basalt in the crust beneath the plain [e.g., *Sparlin et al.*, 1982], which caused it to subside. Most of the silicic volcanic rocks are progressively younger to the northeast at a rate of 35 to 40 $mm \cdot yr^{-1}$ as a result of southwestward plate migration over the plume [*Christiansen and Lipman*, 1972; *Armstrong et al.*, 1975]; in contrast to the silicic volcanism, basaltic magmatism has persisted across the plain through Holocene time [e.g., *Luedke and Smith*, 1983; *Leeman*, 1988]. Volcanic rift zones cross the eastern Snake River Plain parallel to the strike of regional normal faulting (Plate 1), and are thought to be the surface expression of dike complexes at depth [e.g., *Kuntz et al.*, 1992; *Hackett and Smith*, 1992]. Significantly, young basaltic volcanism is not restricted to the plain but has also occurred within the transition zone of the eastern Snake River Plain (Plate 1) with many vents younger than 100,000 years in the transition zone south of the plain [e.g., *Luedke and Smith*, 1983]. Broadly distributed volcanism across plume tracks is not uncommon; for example, plume-related volcanism is observed discontinuously over areas 500 km or more across at Hawaii, the Canary Islands, and Iceland [e.g., *Lipman et al.*, 1989].

2.3. Faulting

Small earthquakes at shallow focal depths (< 8 km) within the eastern Snake River Plain are inferred to result from elastic failure of a thin seismogenic crust [*Jackson et al.*, 1993], but the lack of developed fault-block topography on the plain suggests the offsets from such failures are minor. Outside the eastern Snake River Plain, *Pierce and Morgan* [1992] have categorized faulting in its transition zone by age and offset into four neotectonic belts surrounding the plain. The first or outer belt is characterized by small-offset Holocene normal faults and surrounds the eastern Snake River Plain approximately 200 km from the topographic edge of the plain. The second belt, consisting of major Holocene normal faults, surrounds the eastern Snake River Plain at about 100 km from its edges. The third belt characterized by late Pleistocene faults is found immediately along the northern edge of the transition zone of the eastern Snake River Plain but fades to between 50 and 100 km away along the southern transition zone. Major faults in these three belts are shown in Plate 1. The fourth belt identified by *Pierce and Morgan* [1992] consists primarily of Tertiary-aged faults and is found along the southern transition zone of the plain. This area coincides with a zone of reduced seismicity at the southern edge of the eastern Snake River Plain (Plate 1). In general, the northern transition zone of the eastern Snake River Plain has a history of more recent (Holocene) fault activity than does the southern transition zone. The horizontal spacing of normal faults becomes closer nearer to the edges of the eastern Snake River Plain [*Pierce and Morgan*, 1992], which may be an indication that the depth to alternate extensional strain mechanism (ductile flow or magmatism) shallows toward the plain.

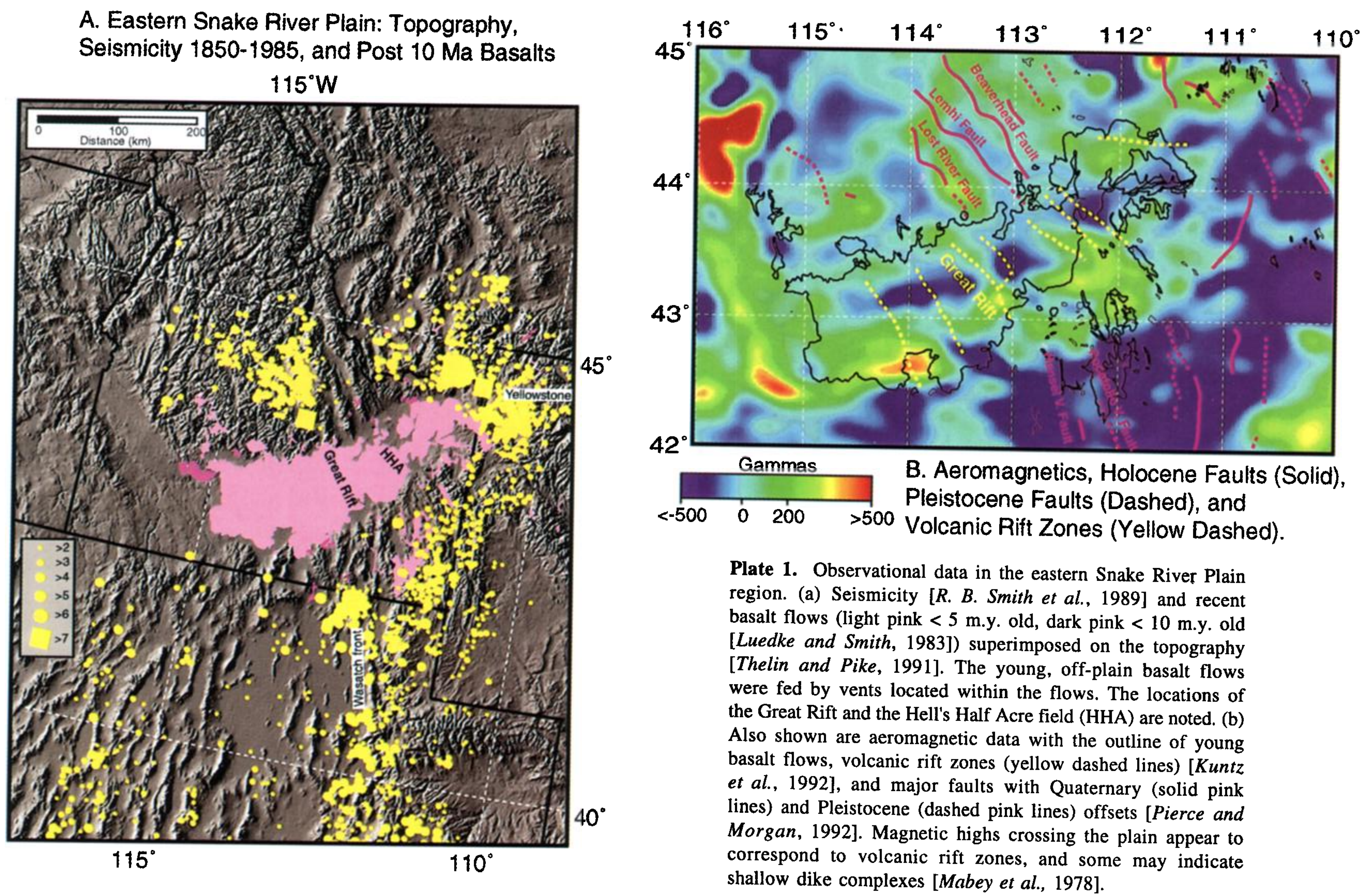

Plate 1. Observational data in the eastern Snake River Plain region. (a) Seismicity [*R. B. Smith et al.*, 1989] and recent basalt flows (light pink < 5 m.y. old, dark pink < 10 m.y. old [*Luedke and Smith*, 1983]) superimposed on the topography [*Thelin and Pike*, 1991]. The young, off-plain basalt flows were fed by vents located within the flows. The locations of the Great Rift and the Hell's Half Acre field (HHA) are noted. (b) Also shown are aeromagnetic data with the outline of young basalt flows, volcanic rift zones (yellow dashed lines) [*Kuntz et al.*, 1992], and major faults with Quaternary (solid pink lines) and Pleistocene (dashed pink lines) offsets [*Pierce and Morgan*, 1992]. Magnetic highs crossing the plain appear to correspond to volcanic rift zones, and some may indicate shallow dike complexes [*Mabey et al.*, 1978].

2.4. Potential Field Data

The Snake River Plain is a regional magnetic high, with a positive anomaly along its southern edge and a negative anomaly along its northern edge. This pattern is consistent with a flat-lying tabular magnetized plate and probably results from the basalt lava flows that cover the eastern Snake River Plain. Positive anomalies are also identified crossing the eastern Snake River Plain, and some can be correlated with rift zones and basalt vents [e.g., *Mabey et al.*, 1978], the best example being the magnetic high associated with the Great Rift; it extends many kilometers north of the plain into the Pioneer Mountains (Plate 1). The magnetic anomalies that cross the plain are subparallel to regional normal faulting and volcanic rift zones and may represent dike complexes at depth. These plain-crossing magnetic anomalies appear also to extend across the topographic boundaries of the eastern Snake River Plain (Plate 1), particularly to the south where young basalts have been erupted. The Snake River Plain also represents a gravity high (both Bouguer and Isostatic Residual), probably because of the large volume of relatively dense basalt intruded into the crust. The strongest positive Bouguer anomaly lies in the western Snake River Plain and fades gradually to the east, suggesting a growing accumulation of basaltic input to the crust with time as the North American Plate tracked southwest over the Yellowstone plume.

3. Role of the Yellowstone Plume in the Extension and Uplift of the Northern Basin and Range Province

The northern Basin and Range is presently one of the most actively extending parts of the province, particularly around the eastern Snake River Plain as evidenced by greater seismicity there (Plate 1). It has been suggested that the Yellowstone plume plays an important role in the uplift and extension of the northern Basin and Range Province both through deep-seated mantle effects as well as increased crustal magmatism [e.g., *Hill*, 1991; *Anders and Sleep*, 1992; *Pierce and Morgan* 1992; *Parsons et al.*, 1994]. Recent advances in the understanding of mantle plume behavior and dynamics worldwide help to identify the likely effects of the Yellowstone plume on the northern Basin and Range Province and eastern Snake River Plain. Perhaps the two most ubiquitous manifestations of mantle plumes are voluminous magmatism and a broad regional topographic swell. The typical swell associated with plumes is ~1-2 km of uplift centered across a region ~1000-2000 km in diameter [e.g., *Crough*, 1979; *Sleep*, 1990], which is the result of isostatic compensation in the asthenosphere and lithosphere and, to a lesser extent, a dynamic pressure gradient of flow in the asthenosphere (below the limit of detection at Hawaii) [*Sleep*, 1990].

The interpreted anatomy of a mantle plume consists of a starting plume head generated during its initial ascent through the mantle, an active plume tail that continues to flow after the starting plume head contacts the lithosphere, and ponded plume-tail material that collects as the active plume tail continues to flow [e.g., *Griffiths and Campbell*, 1991]. The initial contact of the starting plume head with the lithosphere heats a broad region because the plume head is much wider than its tail [e.g., *Duncan and Richards*, 1991]. The starting plume head and the active tail may drift independently in the asthenosphere, causing the active plume tail to contact the lithosphere away from the center of the starting plume-head swell [e.g., *Griffiths and Campbell*, 1991]. When a hotspot swell forms in continental lithosphere, the uplifted crust may be raised far enough above the level of midplate compression from the ridge push force to be in a state of extension, which results in rift formation centered in the swell [*Crough*, 1983, *Houseman and England*, 1986]. The magnitudes of these generated deviatoric stresses probably fall short of those necessary to cause complete continental breakup [*Hill*, 1991].

The buoyancy and swell associated with the starting plume head tend to move with the lithospheric plate [*Sleep*, 1990; *Griffiths and Campbell*, 1991]. The heat associated with mantle plumes tends to be contained in the mantle near the plume for a considerable time. For example, *Davies* [1992] concluded that the thermal anomaly associated with the Hawaiian plume has not waned appreciably during its 43-m.y. existence because the swell does not decay monotonically with distance along the volcanic chain as would be the case in a thermal decline with age. That is, the material hotter than the normal mantle adiabat may remain ponded below the lithosphere and above normal mantle because of the long time required for heat applied at the base of the lithosphere to conduct to the surface and because secondary convection within the thermal boundary created by plume material is inefficient.

The Yellowstone plume province manifests many of the usual characteristics of continental plume provinces worldwide; the Yellowstone plume erupted the voluminous Columbia River flood and Steens Mountain basalts and emplaced the dike swarm of the northern Nevada rift; it formed a hotspot track and caused a regional swell, and the active plume tail continues to supply hot material, causing magmatism, uplift, and extension progressing eastward relative to North America [e.g., *Pierce and Morgan*, 1992; *Geist and Richards*, 1993; *Anders*, 1994]. The tomographic velocity images of *Saltzer and Humphries* [1997] show a narrow, relatively low velocity conduit beneath the Snake River Plain that is consistent with the concept of an active plume tail embedded in broadly distributed, older, cooler starting-plume-head asthenosphere. *Anders and Sleep* [1992] calculated the transient thermal effects of the plume on the rate of extensional strain and found that rapid strain rate increases were a likely consequence of intrusive magmatic pulses into the crust. The increased strain rates are suggested to result from a temporary thermal softening in the crustal rheology as well as mantle-driven isostatic uplift and are correlated with observed transient increases in fault offsets in the eastern Snake River Plain transition zone [*Anders and Sleep*, 1992]. Subsequent cooling, and hence strengthening, of intrusive rocks is then suggested to have caused the apparent tectonic quietude in the eastern Snake River Plain and transitions. We focus here on the behavior of the eastern Snake River Plain and surrounding transition zone after the passing of the Yellowstone plume tail.

4. The Eastern Snake River Plain and Margins in Context of Regional Balanced Strain

We make the assumption that broadly (areally along a line about 100 km long and vertically over the thickness of the crust) there must be balanced extensional strain. This implies that areas of large-magnitude strain cannot be adjacent to areas of no strain without some form of accommodation zone such as a fault between them. Thus, while fault-bounded blocks within the Basin and Range Province may be undeformed internally, the cumulative strain across the province along any 100-km line length is of the same order of magnitude as another line along a comparable azimuth. We base this assumption on the elastic strength limit of the crust, and it is borne out observationally [e.g., *Parsons*, 1995, and references therein].

4.1. Horizontal Strain Balance

The low seismicity and lack of major faulting in the eastern Snake River Plain and transition zone indicate that despite being situated within the regionally extending Basin and Range Province, the plain accommodates strain in a different manner from its surroundings. If the eastern Snake River Plain is coupled to the Basin and Range Province, then it must strain at the same average rate as its surroundings over time. If the eastern Snake River Plain is not coupled to the Basin and Range Province, then some form of accommodation zones such as strike slip faults are necessary for long-term regional strain balance. However, despite the abrupt truncation of topographic relief along the boundaries of the plain, the trends of ranges and basins do not change as they might if dragged along a strike slip zone [*Rodgers et al.*, 1990]. Moreover, seismic focal-mechanism studies indicate that extensional strain dominates in the transition zone of the eastern Snake River Plain [e.g., *Doser and Smith*, 1985; *Peyton et al.*, 1991], and within the Plain itself [*Jackson et al.*, 1993]. Additionally, regional mapping and fault investigations along the northwestern margin of the plain have failed to recognize active plain-parallel faulting of any kind [*Breckenridge and Othberg*, 1991; *Golder and Associates*, 1992; *Zenter*, 1989].

The trends of the basin-range pairs in the Basin and Range Province are variable, indicating that extension directions (roughly perpendicular to range trends) are also variable (Figure 1). For example, the eastern Snake River Plain and transition zone appear to be extending in a southwest direction, whereas extension is directed more northwesterly in central Nevada. The Yellowstone hotspot may have redirected extension in its vicinity because of a topographic swell caused either by hot upper mantle [e.g., *Anders and Sleep*, 1992; *Pierce and Morgan*, 1992] or by some component of buoyancy from depleted upper mantle [e.g., *Saltzer and Humphreys*, 1997]. Broadly distributed right- and left-lateral strike slip shear zones in the western Basin and Range Province appear to accommodate the variable extension directions [e.g., *Pezzopane and Weldon*, 1993, and references therein].

In order to estimate the likely strain rate within the eastern Snake River Plain and to calculate the differential stress magnitude predicted to develop in the event that the plain does not strain or strains elastically with its surroundings, we calculated and compiled strain rate estimates for the region surrounding the plain (Table 1). Estimates from a variety of sources converge to an average strain rate of about 5.3×10^{-16} s^{-1} (from a range of $2.9\text{-}8.2 \times 10^{-16}$ s^{-1}). We calculate using the method of *Kusznir and Park* [1987] that the predicted magnitude of elastic differential stress could reach as high as 600 MPa in 10 m.y. if the hot (heat flow of ~100 mW m^{-2}) eastern Snake River Plain crust has been resisting a strain rate of 5×10^{-16} s^{-1} (Figure 2). The typical stress drop from a normal-fault earthquake is much less at 1-10 MPa [e.g., *Kanamori and Anderson*, 1975; *Jackson and Blenkinsop*, 1993], suggesting that crustal rocks do not have the strength to resist such stresses. Even if relatively strong basalt has intruded and strengthened the eastern Snake River Plain midcrust, it would not endow the crust with the orders of magnitude greater strength increase necessary to withstand the stresses applied by regional strain. Instead, extensive mafic intrusion might add about a 100% strength increase in uniaxial compression, about a 40% strength increase in tension [e.g., *Bredthauer*, 1957; *Jaeger*, 1960, *Brace*, 1964], and only about a 10% strength increase at higher temperatures [*Handin*, 1966]. Direct observational evidence of low differential stress on the plain is provided by a borehole at the Idaho National Engineering Laboratory, which penetrated the basalt flows and ash flow tuffs to a depth of more than 3 km; an acoustic borehole televiewer study reported no stress-induced breakouts in the silicic volcanic sequence between 2066 and 3122 m depth [*Moos et al.*, 1990], an indication of low differential stress.

If the eastern Snake River Plain strains magmatically by vertical dike intrusion, then we can develop estimates for strain rates inside the plain based on surface and drill hole observations. Because diking is elastic strain, the contribution from dikes that fed unevenly distributed (or nearly collinear) flows is additive, much like repeated earthquakes occurring at a group of unevenly distributed fault zones act to accommodate regional elastic strain release. During the past 15,000 years between the Great Rift and the Hell's Half Acre volcanic field (75 km, Plate 1), there were 11 total eruptive events (eight at the Craters of the Moon field, and one each at the Robbers, Cerro Grande, and Hell's Half Acre fields [e.g., *Kuntz et al.*, 1986, 1992]). Thus, if we assume that each of the 11 major eruptive events on that 75-km-length of the eastern Snake River Plain were fed by 1-to 2-m-thick dikes (*Kuntz* [1992] reports a 1-to 2-m-range observed in three eastern Snake River Plain lava fields), then we find strain rates ranging from 3.1×10^{-16} s^{-1} to 6.2×10^{-16} s^{-1}.

In the simple analysis above, dikes are assumed to cross the entire plain, and only dikes that reached the surface are included; in reality, more complex dike systems intrude the plain [e.g., *Kuntz*, 1992], though volcanic rift zones do cross the entire plain in most cases. If we attempt to quantify dike-driven extension in three dimensions, we could apply the average dike length as calculated by *Kuntz* [1992] of 5-10 km or 10-20% of the width of the plain. However, we would need to quantify how many dikes intruded that did not quite reach the surface (global intrusive-to-extrusive volume estimates for basalt suggest a 10-to-1 ratio [e.g., *Crisp*, 1984]). Unfortunately, determining a useful number of noneruptive dikes is not possible. However, we can use dike-length estimates to calculate minimum strain rates if we assume

Table 1. Strain Rates in the Northern Basin and Range Province and Eastern Snake River Plain for Time Intervals During the Past 16 m.y.

Strain Rate s^{-1}	Time Interval	Basis	Location	References
3.80×10^{-16} ($1 cm\ 800 km^{-1}\ yr^{-1}$)	present	plate motions and space geodesy	northern Basin and Range: Colorado Plateau to Sierra Nevada	1, 2, 3
3.80×10^{-16} ($1 cm\ 800 km^{-1}\ yr^{-1}$)	historical earthquakes	summation of seismic moments	northern Basin and Range	4, 5
6.30×10^{-16} ($10.7 km\ 52 km^{-1}\ 10 Myr^{-1}$)	10 Ma +/- 4 my	lateral and vertical offsets of northern Nevada rift	north central Nevada	6, 7
7.90×10^{-16} ($10 m\ 30 km^{-1}\ 12 kyr^{-1}$)	Holocene	offsets of 12 kyr old lake shoreline; 30 km between ridge crests	Dixie Valley, northern Nevada	8
4.10×10^{-16} ($3 km\ 30 km^{-1}\ 8 Myr^{-1}$)	8 Ma	offset of 8 Myr old basalt; 30 km between ridge crests	Dixie Valley, northern Nevada	9
2.90×10^{-16} ($4 m\ 27 km^{-1}\ 15 kyr^{-1}$)	15 ka	two offsets of 15 Kyr old alluvial surface by Lost River fault; 27 km between ridge crests	Site of 1983 Borah Peak earthquake north of eastern Snake River Plain (Thousand Springs segment)	10
8.20×10^{-16} ($\sim 14 km\ 80 km^{-1}\ 7 Myr^{-1}$)	7 Ma (age of calderas longitude Lost River Fault)	dip of faults taken to be 50° and strata 15°. Three tilt blocks spanning 80 km.	three tilt-block ranges north of eastern Snake River Plain (Lost River, Lemhi, and Beaverhead Ranges, Idaho)	5,.11
3.10×10^{-16} to 6.20×10^{-16} (8 to $16 m\ 75 km^{-1}\ 15 kyr^{-1}$)	15 ka	11 eruptions in 4 lava fields in past 15 kyr, each fed by a 1-to 2-m dike.	eastern Snake River Plain. Great Rift to Hell's Half Acre lava field	12, 13
1.1×10^{-15} to 2.2×10^{-15} (11.7 to $23.4 km\ 75 km^{-1}\ 4.5 Myr^{-1}$)	4.5 Ma	total number of lava flows, each fed by a 1-to 2-m dike	eastern Snake River Plain; Arco volcanic rift zone to Lava Ridge-Hell's Half Acre volcanic rift zone	13, 14, 15, this paper

References are as follows: 1, *De Mets et al.* [1990]; 2, *Minster and Jordon* [1987]; 3, *Beroza et al.* [1985]; 4, *Eddington et al.* [1987]; 5, *R. B. Smith et al.* [1989]; 6, *Zoback* [1978]; 7, *Zoback* [1979]; 8, *Thompson and Burke* [1973]; 9, *Okaya and Thompson* [1985]; 10, *Scott et al.* [1985]; 11, *Thompson* [1960]; 12, *Kuntz et al.* [1986]; 13, *Kuntz et al.* [1992]; 14, *Hackett and Smith* [1992]; 15, *Hackett et al.* [1991].

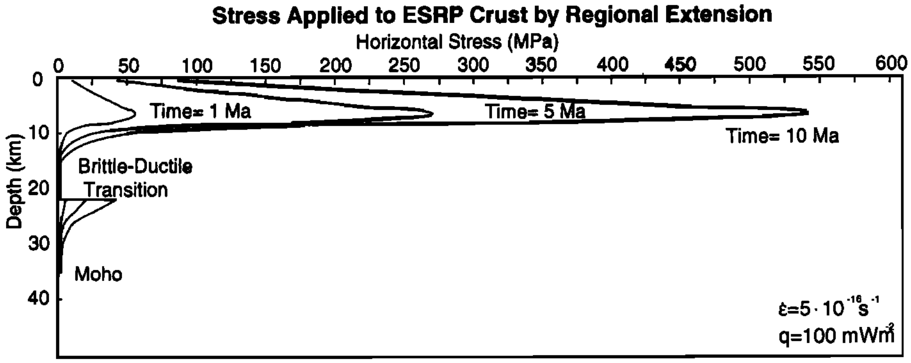

Figure 2. Theoretical build-up of differential stress in the brittle upper eastern Snake River Plain crust if the rocks are strong enough to resist regional extensional strain over time periods of 1, 5, and 10 m.y. The lithosphere is treated as a Maxwell viscoelastic solid where stress and strain are linked through the equation $\varepsilon_x = \frac{1}{E}(\sigma_x - \sigma_x^o) - \frac{\nu}{E}(\sigma_y - \sigma_y^o) - \frac{\nu}{E}(\sigma_z - \sigma_z^o) + \varepsilon_x^\nu$, where ε is strain ($\varepsilon_x^V$ is ductile creep in the x direction), σ is stress (σ_x^o is initial stress), E is Young's modulus, and ν is Poisson's ratio (see *Kusznir and Park*, [1984,1987] for complete details on the method). Applying a strain rate of 5.0×10^{-16} s^{-1} over time yields extremely high stresses in the upper crust that far exceed the observed 1-to 10-MPa stress drop for normal-fault earthquakes [e.g., *Kanamori and Anderson*, 1975; *Jackson and Blenkinsop*, 1993].

randomly distributed dike events across the plain over time. A minimum surface estimate for magmatic strain rate is 3.1×10^{-17} s^{-1} if all the flows were fed by the thinnest (1 m) and shortest (5 km) estimated dikes without any accompanying noneruptive diking. Indications are that many dikes on the eastern Snake River Plain are much longer than 5 km as evidenced by >20-km-long surface fissures associated with the Craters of the Moon volcanic field; many of these might be longer than 20 km as they are covered by young basalt flows. Even if the most conservative estimates are applied, the calculated strain rates by magmatism along the eastern Snake River Plain are at the appropriate orders of magnitude as compared with rates outside the Plain for the past 15,000 years (see Table 1).

Longer-term strain rates can be calculated by estimating the total volume of extruded basalt in a sample area (the Idaho National Engineering Laboratory, where three deep drill holes and statistical analyses of lava flow dimensions exist [*Hackett and Smith*, 1994; *Hackett et al.*, 1991]). From this exercise we can estimate the total number of dikes that intruded the eastern Snake River Plain (across a 75 km length by 50 km width) during the past 4.5 m.y. by dividing the total estimated extrusive volume (3500 km^3) by the average flow volume of ~0.3 km^3 [*Hackett and Smith* 1994; *Hackett et al.*, 1991] to arrive at an estimate of ~11,700 feeder dikes (or ~11.7-23.4 km if a 1-to 2-m-thickness is again assumed for dikes). These values yield a range from 1.1×10^{-15} s^{-1} to 2.2×10^{-15} s^{-1} in long-term strain rate if dikes are assumed to cross the plain. A minimum value limited to only eruptive, 1-m-by-5 km-dikes randomly distributed across the plain is 1.1×10^{-16} s^{-1}. These magmatic strain rate values are again comparable to strain in the surrounding Basin and Range Province during this longer time period (Table 1).

4.2. Vertical Strain Balance

The distribution of active faulting, fault dip, and spacing within the eastern Snake River Plain transition zone is highly variable and may indicate that the deeper mode of ductile extension within the transition zone is correspondingly variable. The observation that in some parts of the transition zone normal faults become more closely spaced with proximity to the eastern Snake River Plain [e.g., *Pierce and Morgan*, 1992] may imply that some alternate mode of extensional strain takes over at an increasingly shallower depth toward the plain. South of the plain where strands of the Pocatello Valley and Hansel Valley faults come closer together, the fault planes are of opposing dip. In such cases the normal faults must terminate or intersect at shallower depths as they become more closely spaced (Figure 3). In the northern transition zone, brittle extension is accommodated by tilt-block faulting on the Lost River, Lemhi, and Beaverhead faults to form half grabens; in this case, fault spacings are irrelevant because the fault planes are roughly parallel and would not intersect. There is some indication that earthquake focal depths are deeper to the north of the plain, where parallel tilt-block faults are active [*Jackson et al.*, 1993]. Beginning at the apparently variable depth that normal faults terminate (base of seismogenic layer), some alternate form of extensional strain must respond to the applied regional tectonic stresses so that the magnitude of strain balances across a vertical section over time.

Two mechanisms have been identified as candidates for alternate extensional strain modes, ductile shear or crustal flow on the one hand and magmatic inflation on the other. In general, there is a well-established correlation between the depth to the base of the brittle, seismogenic layer and the inferred brittle-ductile transition from the crustal geotherm [e.g., *Kirby and Kronenberg*, 1987]. In an elevated thermal regime such as the Basin and Range Province, the predicted depth to the brittle-ductile transition extrapolated from surface heat flow data is about 15-20 km [e.g., *Lynch and Morgan*, 1987], which agrees well with the average depth that seismic activity fades in the province [e.g., *Smith*, 1978]. If the

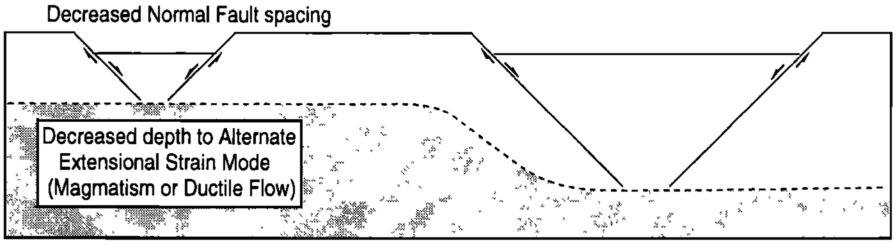

Figure 3. Schematic illustration of the implication of normal-fault spacing on the depth to an alternate mode of extensional strain. When active normal faults of opposing dip are more closely spaced, then either the fault planes terminate at shallower depths, or the faults must cross. The focal depth of earthquakes in the southern transition zone shallows toward the eastern Snake River Plain [e.g., *Jackson et al.*, 1993] where normal faults become more closely spaced [e.g., *Pierce and Morgan*, 1992]. In order for balanced strain to occur, either ductile flow or magmatic intrusions must become the primary strain mode at depth.

extensional system is closed (fixed-volume crust allowing no introduction of new material), then as the crust stretches, it must thin. Since large-magnitude extension in the Basin and Range Province is often recognized at the surface of crust that does not appear to be proportionately thinned, magmatism is commonly suggested as a means to maintain the thickness of the crust as it stretches, for example by underplating thus opening the system to new material [e.g., *Gans*, 1987]. Moreover, the crust of the eastern Snake River Plain is actually thicker than the adjacent Basin and Range Province [*Sparlin et al.*, 1982].

Magmatism can also play a direct role in accommodating extension, because in an extensional stress regime, magma tends to intrude the crust as vertical dikes, perpendicular to the horizontal least principal stress [e.g., *Anderson*, 1951; *Emerman and Marrett*, 1990]. Deeply sourced basaltic melts enter the crust with a strong head of pressure that enables them to oppose the crustal stresses and force open conduits in which to intrude. Rapid freezing of such vertical dikes causes a lasting crustal strain because the conduit is propped open by the frozen basalt within it [e.g., *Parsons and Thompson*, 1991]. The width of a typical dike (1-10 m) is comparable to the coseismic horizontal (extensional) component of slip on a normal fault during a moderate to large earthquake, implying that the stress drop after a normal-fault earthquake is similar to that of a dike event. Because basaltic melts freeze in a matter of days or hours [e.g., *Delaney*, 1987], the strain release of a dike or earthquake event both fall into the elastic mode. The rate of dike propagation, however, is limited by the viscosity of intruding magma, allowing the strain to occur incrementally as the dike tip advances and causing the process to generate only low-magnitude seismic events or to be nearly aseismic [*Smith et al.*, 1996]. In other words, fault motion and intrusive dikes are equivalent mechanisms for increasing the magnitude of the least principal stress (thus decreasing or eliminating the differential stress) in the brittle, seismogenic crust (Figure 4). Magmatism also has the effect of advecting heat from the mantle directly into the crust far more efficiently than slow thermal conduction, and this advected heat can help stimulate ductile crustal flow and decrease the depth to the brittle-ductile transition.

5. Evaluation of Models for the Evolution of the Eastern Snake River Plain and Margins

5.1. Weak Crust: Ductile Eastern Snake River Plain Models

Models that attribute the extension in the eastern Snake River Plain to a more mobile crustal rheology resulting from the heat input from the Yellowstone plume [e.g., *Furlong*, 1979; *Brott et al.*, 1981] allow for strain balance between the Basin and Range Province and eastern Snake River Plain achieved by aseismic creep in the plain decoupled from brittle extension on normal faults in the Basin and Range. Small earthquakes within the eastern Snake River Plain contribute insignificantly to upper crustal strain but show that the upper crust is seismogenic to their maximum depth of about 8 km, which corresponds well with the interpreted depth to the brittle-ductile transition from surface heat flow [e.g. *Brott et al.*, 1981; *Jackson et al.*, 1993]. However, the number of events is very small and may not be enough to constrain the depth to the brittle-ductile transition within the plain. Thus, although ductile flow in the crust undoubtedly occurs at depth beneath the hot eastern Snake River Plain, it cannot account for the extension of the brittle uppermost crust which is estimated to be about 8 km thick. The even hotter Yellowstone Plateau area has many earthquakes (Plate 1) confined to a brittle crust that is only about 5 km thick [e.g., *Smith*, 1978]. Similarly, in east Africa where another continental hotspot (caused by the Afar plume) affects the crust, comparably small elastic plate thicknesses correspond to areas of impressive normal fault scarps [e.g., *Ebinger et al.*, 1989], in strong contrast to the low relief of the eastern Snake River Plain. Thus, if the whole crust strains uniformly over time, then some alternate extensional mechanism must operate in the uppermost crust.

5.2. Strong Crust: Rigid Eastern Snake River Plain Models

Although the geologic evidence of a lack of strike slip motion along the edges of the plain appears to rule out models in which the plain acts as a rigid kernel encased in an

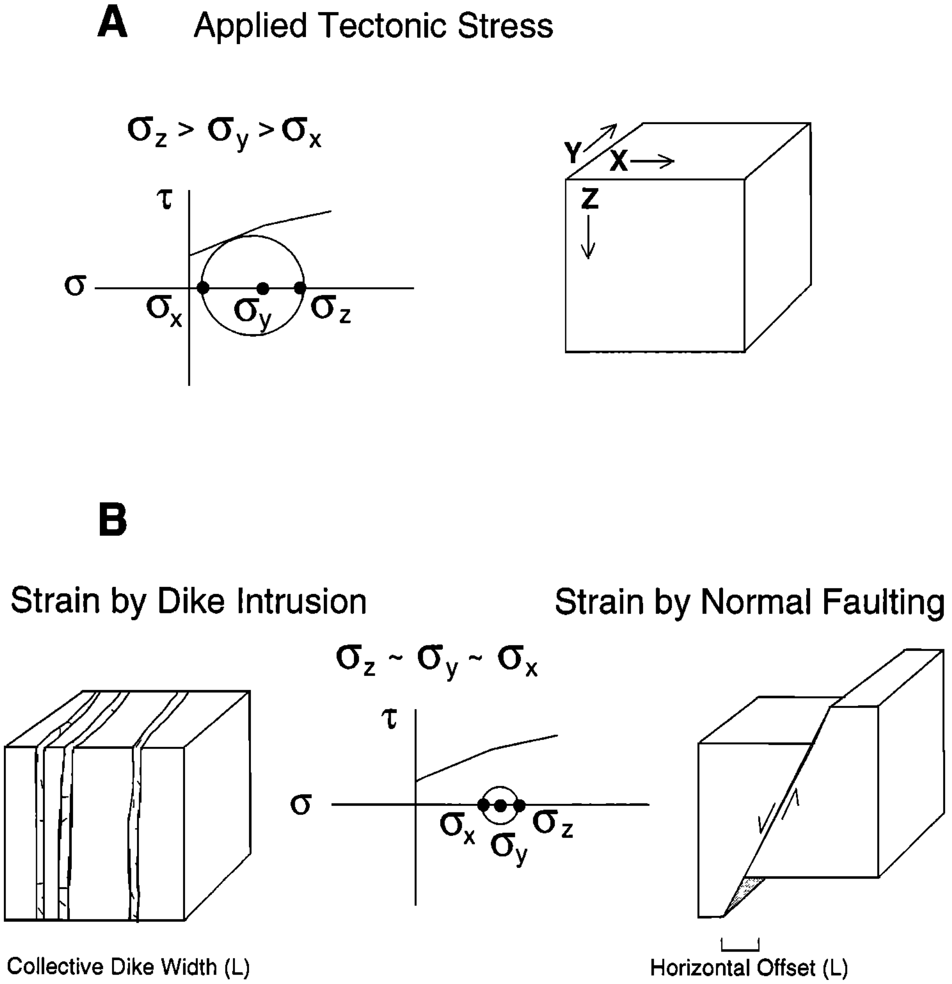

Figure 4. (a) Given an applied tectonic stress such that the greatest principal stress is vertical (σ_z) and equals the lithostatic load and the least principal stress is horizontal (σ_x), failure will occur when the differential stress (diameter of the Mohr circle) touches the Coulomb envelope. (b) To relieve the buildup in stress, two different modes of strain can occur over the elastic time frame, a normal fault with horizontal displacement L or, if sufficient magma supply exists, dikes of collective width L. After strain occurs, the vertical greatest principal stress is unchanged, while the horizontal stresses are increased, causing a net reduction in the differential stress. The Mohr circle no longer touches the failure envelope and faulting ceases. Continued application of stress causes multiple repetitions in the cycle. Depending on magma supply, some combination of dike intrusion and normal faulting may act in concert to accommodate the extensional strain.

extending Basin and Range terrane, we review this model in terms of applied stress. A consequence of persistent basaltic volcanism on the plain is a likely increase in its strength after cooling [e.g., *Anders et al.*, 1989; *Smith and Arabasz*, 1991] since much of the upper to midcrust may have been replaced by stronger mafic intrusive rocks [e.g., *Sparlin et al.*, 1982]. An increase in strength is predicted with time at any point along the eastern Snake River Plain since much of the crustal replacement may have occurred near the transient position of the Yellowstone plume, and subsequent cooling of the intrusive rocks implies a strength increase [e.g., *Anders and Sleep*, 1992]. We calculated the magnitude of stress buildup that would accumulate in the upper crust for various times over a 10-m.y. time interval (Figure 2), assuming extension at the same rate as the surrounding Basin and Range Province. The results indicate that to resist faulting, the eastern Snake River Plain crust would need to be 10 to 60 times stronger than the surrounding Basin and Range crust, assuming that a 10-MPa stress drop characterizes the average normal-fault earthquake [e.g., *Kanamori and Anderson*, 1975; *Jackson and Blenkinsop*, 1993]. Laboratory measurements carried out at pressures up to 500 MPa and temperatures up to 500°C on the ultimate strength of a variety of basalts, diabases, and gabbros compared to more silicic granites and gneisses indicate on average only about a 10% increase in strength for the more mafic rocks [*Handin*, 1966]. Low-pressure, low-temperature tests showed, on average, about a 100% strength increase in uniaxial compression and about a 40% strength increase in tension for mafic rocks over more silicic rocks [e.g., *Bredthauer*, 1957; *Jaeger*, 1960, *Brace*, 1964]. Clearly, crustal composition is only one factor in determining the regional strength of the eastern Snake River Plain; the degree of fracturing and pore fluid pressure may be as or more important. However, consideration of the facts that microearthquakes do occur within the plain [*Jackson et al.*, 1993] and that dating of volcanic rocks combined with plate motion rates show the plain has extended during the past 16 m.y. [*Rodgers et al.*, 1990] indicates that the brittle upper crust of the plain has not resisted extensional stresses but extends by a relatively aseismic process. Finally, in situ stress indicators show the plain to be in a low differential stress state [*Moos et al.*, 1990], as would be the case if dikes sporadically intrude perpendicular to the least principal stress and reduce the differential stress.

5.3. The Preferred Model: Magmatic Strain

5.3.1. Eastern Snake River Plain interior. Since the upper crust of the eastern Snake River Plain is evidently brittle, it cannot extend by ductile flow, and since the brittle crust is not strong enough to have resisted extensional stresses, we suggest that the upper crust has extended primarily by dike intrusion since the passage of the Yellowstone plume in accordance with the direct observational evidence of volcanic rift zones with characteristic vent chains, fissures, and small grabens crossing the plain. The eruption of widespread young basalts that cover much of the eastern Snake River Plain indicate an excess magma supply of sufficient pressure to erupt to the surface. Such high pressure also enables the melt to oppose the horizontal stresses in the crust, causing lasting strains. When vertical dikes approach the surface they often create small rift grabens directly above the dike, a consequence of the rocks above the dikes extending to match the opening caused by the dike at depth [e.g., *Rubin and Pollard*, 1988]. Grabens of this type are found trending across the eastern Snake River Plain parallel to the strike of normal faults in the surrounding transition zone outside the plain (Plate 1) and perpendicular to the inferred horizontal least principal stress [e.g., *Zoback and Zoback*, 1989]. The youngest volcanic rift zones are near sites of major Quaternary fault activity in the surrounding transition zone, while the older, more poorly defined rifts correlate with zones of late Tertiary faulting [*Kuntz et al.*, 1992]. The volcanic rift zones do not line up exactly with the positions of the adjacent normal faults, indicating that they are independent features (the dikes are vertical and the faults inclined). However, the coincident levels of volcanic and fault activity suggest that horizontal strain balance in the brittle crust is achieved by increased magmatic intrusion into the eastern Snake River Plain, matching the fault activity outside the plain.

We calculate using an average strain rate of 5.4×10^{-16} s^{-1} (Basin and Range estimates from Table 1) that to keep pace with long-term regional extension, about 6.8 m of distributed dike width per 1000 years would need to be intruded across the 400-km length of the eastern Snake River Plain, within an order of magnitude of the calculated range of 2.9 m $k.y.^{-1}$ to 27.7 m $k.y.^{-1}$ from observed surface volcanism (Table 1). Such continuing sporadic dike intrusion (with accompanying horizontal intrusions) would have the effect of raising the thermally controlled level of the brittle-ductile transition and in concert with ductile flow beneath the brittle-ductile transition would effectively accommodate all of the extensional strain throughout the whole crust and perhaps through the whole lithosphere, depending on the magmatic source depth.

5.3.2. Eastern Snake River Plain transition zone. Many different types of data indicate that outside the abrupt topographic boundary of the eastern Snake River Plain there lies a zone that is transitional in character between the interior of the eastern Snake River Plain and the Basin and Range Province. In particular, the transitional zone is generally seismically quiet for a distance of about 50-70 km away from the topographic edges of the plain (Plate 1). Young, small-volume basaltic vents are also observed within the transition zone of the eastern Snake River Plain, both north and south of the plain [e.g., *Fiesinger et al.*, 1982; *Luedke, and Smith*, 1983] (Plate 1), and some of the magnetic anomalies that correspond to volcanic rift zones [e.g., *Mabey et al.*, 1978] extend across the topographic boundaries of the plain (the Great Rift, for example, Plate 1). The focal depth of seismic activity deepens across the transition zone of the eastern Snake River Plain from a maximum of 8 km inside the plain to about 14 km depth beneath the southern transition zone and 17-18 km beneath the northern transition zone [*Jackson et al.*, 1993], indicating that the brittle-ductile transition deepens outside of the plain (subject to the uncertainties associated with the sparse number of events within the plain). We thus suggest that magmatism continues to have a role in accommodating extension in the transition zone of the plain, although with a reduced contribution compared with the interior eastern Snake River Plain, making complementary faulting and magmatism necessary for strain balance (Figure 5).

Outside of the plain, scattered basaltic vents and flows combined with occasional seismic activity extending to increasing depths in the transition zone indicate coupled extensional strain modes of magmatism and faulting acting coincidentally, depending on magma supply (Figure 5). Normal faulting appears to be the dominant strain mechanism away from the transition zone of the eastern Snake River Plain, where mantle isostatic effects related to the emplacement of hot plume material cause uplift and increased extensional activity, while crustal magmatism is reduced.

6. Conclusions

Any model for the evolution of the eastern Snake River Plain must include some explanation for how its brittle upper crust can be coupled to the extending northern Basin and Range Province without faulting. We conclude that it is unrealistic to assume that the eastern Snake River Plain crust is too strong to fail because even strengthened crust and lithosphere could not store the imposed differential stresses without faulting. There is a growing body of published works that suggest that the increased extensional activity and altered extensional direction, relative to the "normal" Basin and Range Province, that surround the eastern Snake River Plain result from the presence of the Yellowstone plume [e.g., *Anders et al.*, 1989; *Anders and Sleep*, 1992; *Pierce and Morgan*, 1992; *Parsons et al.*, 1994]. However, these models do not cpmpletely account for the post-hotspot evolution of the eastern Snake River Plain. The only way that elastic crust

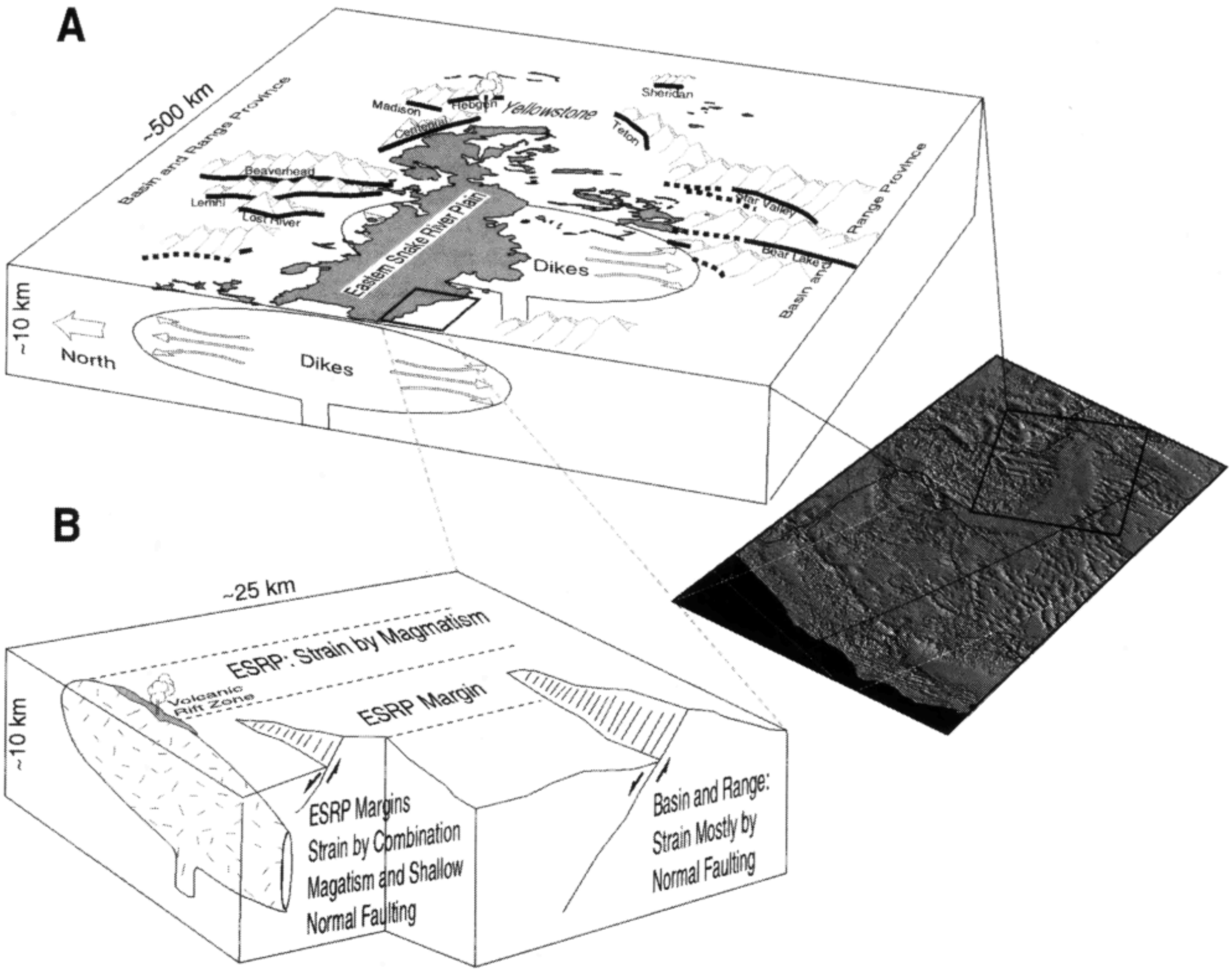

Figure 5. Proposed model for the aseismic elastic strain of the eastern Snake River Plain and transitional behavior of the transition zone of the plain. (a) Regional sketch showing on and off axis volcanism with underlying feeder dike complexes inferred from volcanic rift zones, magnetic anomalies, and the existence of young vents off the central axis of the plain. The dikes are meant to be symbolic in the sketch and are understood to be far more complex than shown [e.g., *Kuntz et al.*, 1992]. (b) Close up sketch showing the proposed variable role of magmatic strain. Within the eastern Snake River Plain we suggest dikes are the primary strain mode because (1) of the lack of developed fault-block morphology, (2) only microearthquakes occur within the plain (magnitudes < 1.5 [e.g., *Jackson et al.* 1993]), (3) in situ stress indicators find low deviatoric stresses [*Moos et al.*, 1990], and (4) of the presence of abundant flood basalts and volcanic rift zones on the plain. Within the transition zone of the plain, highly variable seismicity, ages of fault slip, reduced fault spacing and earthquake focal depths (compared with Basin and Range averages), and variable occurrences of magmatism indicate a transition from magmatic to normal-fault extensional strain. Away from the transition zone, normal faulting becomes the primary strain mode, possibly enhanced by deep-seated isostatic effects caused by the Yellowstone plume [e.g., *Anders and Sleep*, 1992; *Pierce and Morgan*, 1992].

can extend without breaking and shearing is by increased volume. The basalts covering the eastern Snake River Plain indicate an oversupply of magma that could easily fill that volume within the plain. The generally decreasing magmatic input away from the plain and a corresponding increase in faulting and seismicity indicate complementary roles for these two processes of extensional strain within the transition zone of the plain.

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