Rock Mechanics, Daemen & Schultz (eds) © 1995 Balkema, Rotterdam. ISBN 90 5410 552 6

Elastic buckling of fractured basalt on the Columbia Plateau, Washington State

R. A. Schultz
Geomechanics-Rock Fracture Group, Department of Geological Sciences, Mackay School of Mines/172, University of Nevada, Reno, Nev., USA

T. R. Watters
Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, D.C., USA

ABSTRACT: The continental flood basalts of the Columbia Plateau, Washington State, have been deformed into a series of anticlines termed the Yakima Fold Belt. These periodically spaced folds may be associated with buckling instability of a basaltic layer overlying a sedimentary substrate. Previous calculations of critical stress and dominant wavelength of buckling for these rocks assumed the strength properties of intact basalt. Those calculations suggested that buckling required very large modulus contrasts. Here we investigate the effect of using a rock-mass strength criterion and a deformation modulus on simple elastic models for buckling of basalts at the Earth's surface. We find that buckling can be predicted for smaller, more plausible values of modulus contrast. Using revised parameters, the buckling model provides a reasonable explanation for periodic folding in these fractured basalts.

1 INTRODUCTION

Folding of sequences of basaltic lava flows on the Columbia Plateau, Washington State, is a plausible mechanism for forming the Yakima ridges (Reidel et al., 1989a). Although thrust faults have nucleated in the cores of these anticlines (Reidel, 1984), the regular spacing between ridges is consistent with localization and dominant wavelength of folding due to buckling instability at or near the free surface (Watters, 1989).

Previous investigations of folded basaltic rocks from the Columbia Plateau and elsewhere have assumed either elastic (Watters, 1989, 1991) or power-law viscous (e.g., Zuber and Aist, 1990) rheologies for the rocks at the time of fold nucleation. Because these rocks were deformed in the shallow near-surface but at elevated temperatures, a variety of rheologies could apply. We choose to examine an elastic rheology as an approximation to the initial, short term material response.

In order for previous elastic models to predict the proper ridge spacing on the Plateau (12–28 km), large Young's modulus contrasts (plate vs. substrate) that exceed 500 or 1000 are typically required. This result requires that the critical stress for buckling is less than the shear strength of the basaltic plate. Division of the strong basaltic plate into a number of thinner plates with frictionless contacts (Johnson, 1970) is also needed. The requirement of very large modulus contrast has rendered elastic buckling models somewhat limited in their applicability to this problem. As a result, viscous models have been preferred over elastic models for predicting ridge spacing.

Because the strength of the plate is a constraint on elastic buckling models, the choice of strength criterion for the strong basaltic layer is of fundamental importance. Previous work assumed an elastic (basaltic) plate with shear strength limited only by Byerlee's law (Byerlee, 1978), a single plane of weakness model of static frictional strength (Priest, 1993, pp. 276–285). In this paper we assume instead a rock-mass strength envelope based on the Hoek-Brown criterion (Hoek and Brown, 1980) and applied to basaltic lava flows by Schultz (1993, 1995). Evaluation of the rock-mass strength criterion for the strong plate demonstrates that an elastic buckling model can be applied successfully to the stated problem.

2 RELEVANT OBSERVATIONS OF COLUMBIA PLATEAU ROCKS

The Columbia Plateau is the second largest continental flood-basalt province in the world, covering some 164,000 km^2 in the Pacific Northwest region of the United States (Tolan et al., 1989). The basalts studied in this paper occur in central Washington State as part of the Columbia River Basalt Group, which is of Miocene age (16–6 Ma; Reidel et al., 1989a). The basaltic sequence has a maximum thickness of 4 km in the center of the province (Pasco Basin; Reidel et al., 1989a), and is underlain by 1–7 km of Tertiary volcaniclastic and fluvial sediments (Campbell, 1989) that may have been deposited in a series of pull-apart basins (Johnson, 1985; Jarchow et al., 1994). Seismic refraction work (Catchings and Mooney, 1988) documents several (>5–10) low-velocity layers, interpreted as intercalated sediments, within the basaltic sequence. Thin sedimentary interbeds in the basal sequence of the Columbia River Basalt Group, the Grande Ronde Formation, have been observed in well-log data (Reidel et al., 1989a).

Basalts on the Plateau were deformed into a series of anticlines and synclines called the Yakima fold belt (Reidel, 1984). Folding occurred during extrusion of the basalts (Reidel et al., 1989a), as evidenced by ponding and thinning of layers above actively growing folds. Many folds appear to have involved shallow layers. High-angle reverse faults cut the cores of the folds (Reidel et al., 1989a; Jarchow et al., 1994). Anticlines apparently grew toward the free surface; in contrast, synclines are typically flat floored, implying that downward displacement during folding was inhibited. Folds generally strike east-west (Reidel et al., 1989b), normal to the direction of regional maximum horizontal principal stress (Zoback and Zoback, 1980).

Folds in the basalts exhibit regular or periodic spacings (Bentley, 1982; Anderson et al., 1987; Watters, 1989). Fold spacing generally ranges from 12 to 28 km, depending on the particular domain in the Yakima fold belt (Watters, 1989). Average spacing is ~20 km. A periodic spacing implies that a deformation mechanism such as buckling instability due to unstable horizontal compression may be appropriate. A buckling model is also consistent with the orientations of the contemporary stress field in the region.

3 METHOD

3.1 *Stress Analysis*

Buckling of the basaltic sequence is modeled by evaluating the deflection of an elastic plate at the free surface due to an in-plane horizontal end load (Biot, 1961; Turcotte and Schubert, 1982; McAdoo and Sandwell, 1985). The plate rests on a substrate having finite thickness, which in turn overlies a rigid halfspace. Although the degree of involvement of the subjacent halfspace (the crust and/or lithosphere) in near-surface buckling can be an important influence on fold growth and spacing (Zuber and Aist, 1990), this factor is not critical to the present problem, in part because recent seismic and gravity studies show no evidence of basement involvement (Saltus, 1993; Jarchow et al., 1994). Model geometry is shown schematically in Fig. 1; the critical stress for buckling is given by (Watters, 1991)

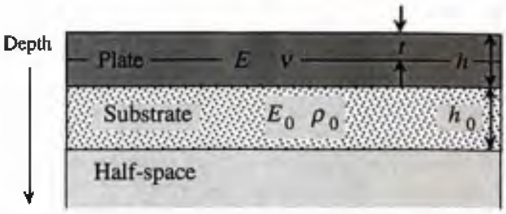

Figure 1. Geometry of buckling model; parameters defined in Table 1 and text.

$$\sigma_{crit} = \left\{\left[\frac{hEE_0}{3(1-\nu^2)h_0 n}\right] + \left[\frac{hE\rho_0 g}{3(1-\nu^2)n}\right]\right\}^{\frac{1}{2}} \qquad (1)$$

in which h, E, and ν are thickness, Young's (or deformation) modulus, and Poisson's ratio of the basaltic plate; h_0, E_0, and ρ_0 are thickness, Young's modulus, and density of the substrate, respectively; n is number of layers; compressive stress is positive; and g is acceleration of gravity. The dominant wavelength of folding is given by

$$\lambda_d = 2\pi\left\{\frac{Enh^3}{12(1-\nu^2)\rho_0 g}\left[\frac{1}{1+\left(\frac{E_0}{\rho_0 g h_0}\right)}\right]\right\}^{\frac{1}{4}} \qquad (2)$$

Values of these parameters are listed in Table 1.

The shear strength of the basaltic plate is given by the Hoek-Brown criterion for fractured rock masses

$$\sigma_1 = \sigma_3 + \left(m\sigma_c\sigma_3 + s\sigma_c^{\,2}\right)^{\frac{1}{2}} \qquad (3)$$

in which σ_1 and σ_3 are the greatest and least principal stresses at the initiation of failure, σ_c is the unconfined compressive strength of intact basalt, m and s are empirical parameters, and compressive stress is positive. We use values for these parameters appropriate to basalts on the Columbia Plateau (Schultz, 1993), as listed in Table 1. Although we recognize that the Hoek-Brown criterion was developed for use only in the shallow near-surface region and for specific engineering applications, this criterion (or one similar to it in form) provides a better representation of rock-mass strength than does a simple Coulomb criterion. The previously used Coulomb-type criterion (Byerlee, 1978) is $|\tau| < 0.85\ \sigma_n$ for $3–5 < \sigma_n <$ 200 MPa. That criterion was then extrapolated to the surface, although its validity there is doubtful.

Buckling can occur according to the elastic model as long as the critical stress for buckling is lower than the frictional strength of the plate. Using a value of Young's modulus for intact basalt (65 GPa), buckling

Table 1. Parameters for buckling model

	Definition	Value
E^*	Deformation modulus of fractured basaltic plate	15–45 GPa
v	Poisson's ratio of plate	0.25
σ_c	Uniaxial compressive strength of intact basalt	262 MPa
RMR	Rock Mass Rating of plate	45–75
m	Hoek-Brown parameter	3.086–9.009
s	Hoek-Brown parameter	0.0022–0.0622
ρ_0	Substrate density	2000 kg m^{-3}
h_0	Thickness of substrate	5000 m
g	Acceleration of gravity	9.8 m s^{-2}

will not occur for thicknesses <2000 m for a contrast E/E_0 <1000 and a number of layers $n < 6$. Thus the critical stress is lower than the Byerlee frictional strength only at a substantial depth and for large modulus contrasts.

3.2 *Estimates of Modulus*

The deformation modulus E^* for basaltic rocks on the Columbia Plateau can be estimated or obtained from several methods. In-situ compressive tests of jointed blocks of Pomona flow basalts from the Hanford site probably provide the best values for deformation modulus. E^* for these 2-m by 2-m by 4.5-m long blocks, with $58 < \text{RMR} < 63$, ranged from 10 to 40 GPa (Department of Energy, 1988). These deformation moduli are smaller than the Young's modulus for intact basalt (83.4 ± 8.3 GPa) by at least a factor of two. A value of Poisson's ratio for the rock or rock mass of 0.25 is consistent with in-situ and laboratory measurements.

Bieniawski's (1989) empirical correlation of RMR and E^* for a variety of rock types is given by

$$E^* = 2\,\text{RMR} - 100 \qquad \text{RMR} > 50 \tag{4}$$

with stated uncertainties of ± 18%. Applied to basaltic rocks (Schultz, 1995), this relation would predict values of deformation modulus of $14 < E^* < 31$ GPa, given the values of RMR above for the jointed block tests. The predicted values are in reasonable agreement with the measured values, as illustrated in Fig. 2.

Measurements of seismic wave velocities from Columbia Plateau rocks provide an independent check on the values of E^* noted above. Seismic refraction experiments (Jarchow et al., 1994) indicate P-wave velocities (V_p) for basalts and underlying sedimentary rock of approximately 5 and 3.5 km s^{-1}, respectively. Velocities of both rock types appear to increase somewhat with depth. In addition, V_p for basalt at the crest of an anticline is ~3.5 km s^{-1}, implying a reduction due to fold-related fracturing. Assuming a value for Poisson's ratio of 0.25, V_p can be converted to dynamic elastic modulus using standard equations (Tutuncu et al., 1994; Fig. 3). Dynamic moduli E_d for basalt and substrate are approximately 30–60 GPa and ~30 GPa, respectively. The dynamic modulus of the basalt is about twice that of the underlying sedimentary rock.

Compressional and shear wave velocities have also been measured underground at the Hanford site. Away from the tunnel face, V_p ~6.2 and 5 km s^{-1} in vertical and horizontal directions, respectively; V_s ~3.3 and 2.5 km s^{-1} (Department of Energy, 1988). These values convert to dynamic Young's modulus and Poisson's ratio of ~80 and 50 GPa, and ~0.3 for these directions. The basaltic rock mass has higher modulus in the vertical direction, parallel to column axes. The dynamic modulus values are comparable to values of

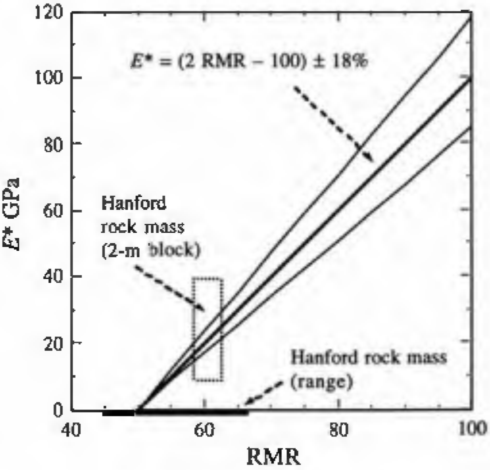

Figure 2. Comparison of measured (box) and predicted deformation moduli from Hanford site basalt vs. RMR. Shaded bar shows range of RMR for basalts.

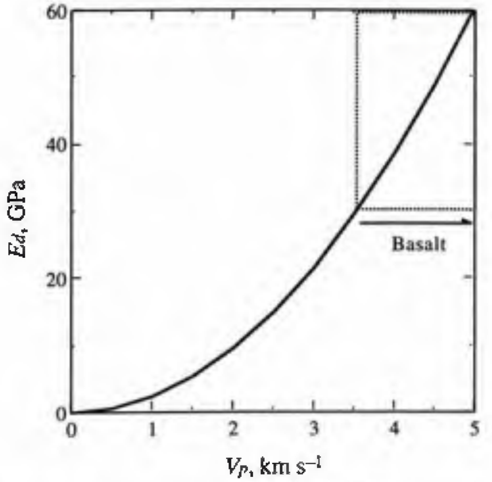

Figure 3. Dynamic Young's modulus E_d vs. compressional-wave velocity V_p showing values for basalts on Columbia Plateau.

static Young's modulus for intact samples of the basalt, and are up to four times greater than deformation moduli for the rock mass (Department of Energy, 1988). These results indicate that the dynamic moduli obtained above in the seismic refraction experiments are probably upper limits to the rock-mass strength for basalt or substrate.

The sediments underlying the basalts are generally poorly consolidated and porous (N. Campbell, pers. comm., 1989). Static moduli of uncompacted dense sand and gravel range from 0.1 to 0.2 GPa (Watters, 1989). Such values could produce a high modulus contrast (50–200) with the basalt. Although compaction due to gravitational loading can increase the modulus (Talwani et al., 1973), this effect can be mitigated by pore water (Mavko and Nolen-Hoeksema, 1994) and variations in RMR or degree of fracturing of the basalts and sediments, as well as degree of lithification of the sediments, at the time of folding. On the other hand, some ambiguity exists in relating dynamic to static moduli (Glynn, 1987) and, perhaps, to deformation moduli. We regard the modulus contrast of two as a lower limit and infer that larger contrasts may have been possible during the deformation.

4 RESULTS AND DISCUSSION

Using the lower and upper limit values of RMR for various basalts from the Columbia Plateau (45 < RMR < 75) and the associated lower and upper ranges of the deformation modulus ($15 < E^* < 45$ GPa), the critical stress and dominant wavelength of buckling were explored for a range of possible deformation moduli for the substrate ($0.1 < E_0 < 0.3$ GPa), thickness of basalt sequence, and number of layers (see Table 1). Buckling of the Columbia River Basalt Group appears to have occurred shortly after the emplacement of the oldest flows, the Grande Ronde (see Reidel et al., 1989a; Watters 1989). The thickness of the Grande Ronde at the Yakima Fold Belt is estimated to be ~2.0 to 3.5 km (see Reidel et al., 1989c). The number of layers n is a critical parameter because a stack of layers with frictionless contacts has a lower critical stress for buckling than that of a single plate of the same cumulative thickness (eq. 1). Thin, mechanically weak, sedimentary interbeds are present in the Grande Ronde basalts and probably facilitated buckling by reducing interface roughness.

The critical stress for buckling was compared to the Hoek-Brown formulation of rock-mass strength

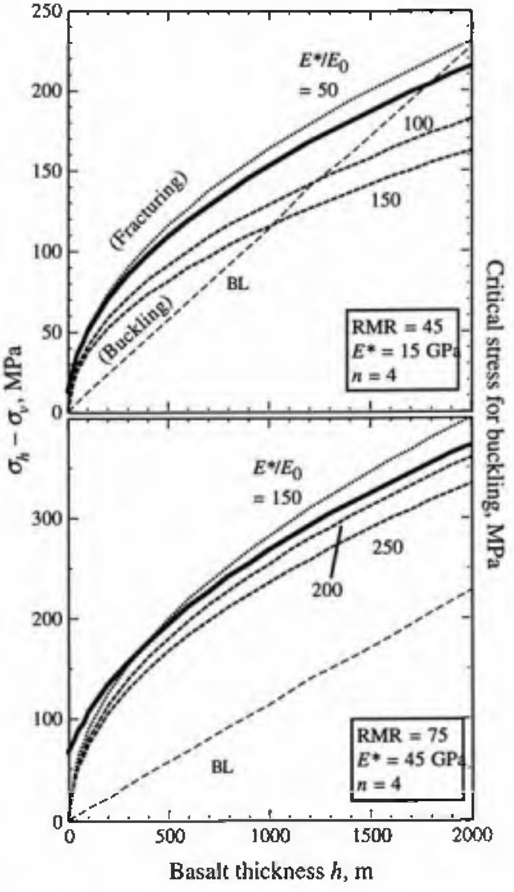

Figure 4. Critical stress for buckling (dashed, dotted curves) vs. thickness of basaltic plate for plausible values of RMR. Plate divided into $n = 4$ layers. BL, Byerlee's law.

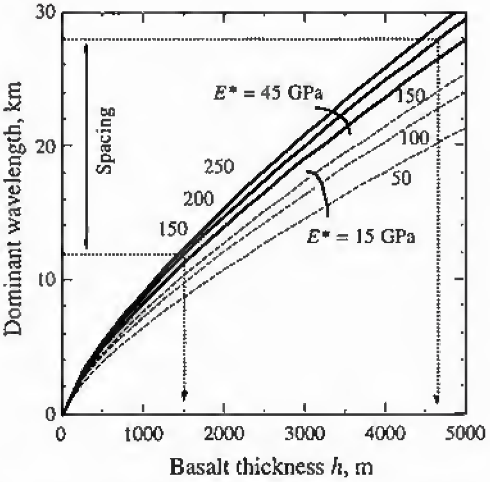

Figure 5. Determination of plate thickness consistent with observed ridge spacing for indicated modulus contrasts.

to determine the range of admissible values for folding. Unlike Byerlee's law, the rock-mass strength criterion is related implicitly to a deformation modulus. Because the critical stress also depends on modulus, the stress and strength expressions are not independent.

For $n = 1$ and 2, buckling is only predicted for very thin plates (< 5 m and <30 m, respectively). At $n = 3$, buckling is limited to a relatively narrow range of parameters. Only a multilayer with a thickness nt of 60 to 130 m will buckle over the range of modulus contrast evaluated ($150 < E^*/E_0 < 250$) for RMR = 75. For RMR = 45, buckling is predicted only at the upper limit of modulus contrast ($E^*/E_0 \geq 150$). In the case of $n = 4$, the range of parameters over which buckling is possible is much broader (Fig. 4). At RMR = 75, buckling is predicted for the entire range of modulus contrast for $nt < 400$ m, and over the entire range of nt for $E^*/E_0 \geq 200$. Comparing these results with those obtained previously using Byerlee's law as the strength criterion, only the highest value of modulus contrast is admissible for $nt > 4300$ m (see Fig. 4). At RMR = 45, buckling is predicted over the full range of modulus contrast (50–150) for $nt < 100$ m, and over the entire range of nt for $E^*/E_0 > 100$. Using only Byerlee's law, buckling is only permitted for $nt > 1500$ m (RMR = 45) or 5000 m (RMR = 75). For $n > 4$, buckling may occur over the entire parameter range when evaluated against the rock-mass strength criterion.

The required contrast in (deformation) moduli between the basaltic plate and sedimentary substrate is much lower than for previous solutions using Byerlee's law. However, plate thicknesses, modulus contrasts, and dominant wavelength of folding should all be consistent with the observations for the model to be considered successful. As shown in Fig. 5, modulus contrasts of ≤250 are sufficient to predict the spacing of ridges on the Columbia Plateau. A plate thickness of 3000–4000 m is implied by the median ridge spacing of ~20 km, comparable to the observed thickness of the basalts.

As noted above, use of a simple Byerlee's law criterion to represent the shear strength of the basaltic plate prohibits buckling of relatively thin multilayers (e.g., <1500 m at $n = 4$, <1800 m at $n = 3$, and < 4000 m at $n = 2$ for RMR = 45) for the range of modulus contrast evaluated (Fig. 4). This implies that thinner basalt sequences cannot buckle. However, field observations do not support this prediction. Secondary (or second-order) folds arranged in echelon sets are developed on the flanks of some of the anticlines (Reidel et al., 1989a). Some of these smaller anticlines and synclines appear to be rooted in relatively thick sedimentary interbeds that occur in the upper section of the Columbia River Basalt Group and involve basalt sequences <500 m thick. Folding of these thinner layers is consistent with the buckling model, assuming a rock-mass strength criterion for the basaltic layer.

5 CONCLUSIONS

We demonstrate that an elastic buckling model, in combination with a rock-mass strength criterion, can satisfactorily predict the spacing and occurrence of folds in near-surface basaltic rocks on the Columbia Plateau. The presence of very large modulus contrasts between basalt and substrate, required in previous elastic models, may no longer be necessary when rock-mass strength is used instead of simple discontinuity strength.

ACKNOWLEDGMENTS

This work was supported in part by NASA's Planetary Geology and Geophysics Program, grants NAGW–2347 and 4151 to RAS, and by grants to TRW. Discussions with R. Watters and S. Reidel on rock-mass properties were very helpful.

REFERENCES

Anderson, J.L., M.H. Beeson & T.L. Tolan 1987. Tectonic evolution of the southwest Columbia Plateau (abstract). *Geol. Soc. Am. Abs. Prog.* 19:354.

Bentley, R.D. 1982. Late Tertiary thin skin deformation of the Columbia River basalt in the western Columbia Plateau, Washington-Oregon (abstract). *Eos, Trans. Am. Geophys. Union.* 63:173.

Bieniawski, Z.T. 1989. *Engineering Rock Mass Classifications.* New York:Wiley, 251 pp.

Biot, M.A. 1961. Theory of folding of stratified viscoelastic media and its implications in tectonics and orogenesis. *Geol. Soc. Am. Bull.* 72:1595–1620.

Byerlee, J. 1978. Friction of rocks. *Pure Appl. Geophys.* 116:615–626.

Campbell, N.P. 1989. Structural and stratigraphic interpretation of rocks under the Yakima Fold Belt, Columbia Basin, based on recent surface mapping and well data. In S.P. Reidel & P.R. Hooper (eds), *Volcanism and Tectonism in the Columbia River Flood-Basalt Province, Geol. Soc. Am. Spec. Pap.* 239:209–222.

Catchings, R.D. & W.D. Mooney 1988. Crustal structure of the Columbia Plateau: Evidence for continental rifting. *J. Geophys. Res.* 93:459–474.

Department of Energy 1988. Consultation draft, site characterization plan, reference repository location, Hanford site, Washington. Report #DOE/RW–0164, vol. 2.

Glynn, E.F. 1987. Elastic moduli of rock: A comparison of in-situ vs. laboratory values. *Proc. 28th U.S. Symp. Rock Mech.*, 223–230.

Hoek, E. & E.T. Brown 1980. Empirical strength criterion for rock masses. *J. Geotech. Eng. Div. ASCE* 106:1013–1035.

Jarchow, C.M., R.D. Catchings & W.J. Lutter 1994. Large-explosion source, wide-recording aperture, seismic profiling on the Columbia Plateau, Washington. *Geophysics* 59:259–271.

Johnson, A.M. 1970. *Physical Processes in Geology.* San Francisco:Freeman, Cooper and Co., 577 pp.

Johnson, S.Y. 1985. Eocene strike-slip faulting and nonmarine basin formation in Washington. In K.T. Biddle & N. Christie-Blick (eds), *Strike-Slip Deformation, Basin Formation, and Sedimentation, Soc. Econ. Paleon. Miner. Spec. Publ.* 37:283–302.

Mavko, G. & R. Nolen-Hoeksema 1994. Estimating seismic velocities at ultrasonic frequencies in partially saturated rocks. *Geophysics* 59:252–258.

McAdoo, D.C. & D.T. Sandwell 1985. Folding of oceanic lithosphere. *J. Geophys. Res.* 90:8563–8569.

Priest, S.D. 1993. *Discontinuity Analysis for Rock Engineering.* London:Chapman and Hall, 473 pp.

Reidel, S.P. 1984. The Saddle Mountains: The evolution of an anticline in the Yakima Fold Belt. *Am. J. Sci.* 284:942–978.

Reidel, S.P., K.R. Fecht, M.C. Hagood & T.L. Tolan 1989a. The geologic evolution of the Central Columbia Plateau. In S.P. Reidel & P.R. Hooper (eds), *Volcanism and Tectonism in the Columbia River Flood-Basalt Province, Geol. Soc. Am. Spec. Pap.* 239:247–264.

Reidel, S.P., K.R. Fecht & T.L. Tolan 1989b. Field Guide to the Lunar and Planetary Institute MEVTV Workshop on "Tectonic Features on Mars:" Structural Features of the Yakima Fold Belt, Columbia Plateau, central Washington, April 22, 1989. Houston:Lunar and Planetary Institute.

Reidel, S.P., T.L. Tolan, P.R. Hooper, K.R. Fecht, M.H. Beeson, R.D. Bentley & J.L. Anderson 1989c. The Grande Ronde Basalt, Columbia River Basalt Group: Stratigraphic descriptions and correlations in Washington, Oregon, and Idaho. In S.P. Reidel & P.R. Hooper (eds), *Volcanism and Tectonism in the Columbia River Flood-Basalt Province, Geol. Soc. Am. Spec. Pap.* 239:21–53.

Saltus, R.W. 1993. Upper crustal structure beneath the Columbia River Basalt Group, Washington: Gravity interpretation controlled by borehole and seismic studies. *Geol. Soc. Am. Bull.* 105:1247–1259.

Schultz, R.A. 1993. Brittle strength of basaltic rock masses with applications to Venus. *J. Geophys. Res.* 98:10,883–10,895.

Schultz, R.A. 1995. Limits on strength and deformation properties of jointed basaltic rock masses. *Rock Mech. Rock Eng.* 28:1–15.

Talwani, P., A. Nur & R.L. Kovach 1973. Compressional and shear wave velocities in granular materials to 2.5 kilobars. *J. Geophys. Res.* 78:6899–6909.

Tolan, T.L., S.P. Reidel, M.H. Beeson, J.L. Anderson, K.R. Fecht & D.A. Swanson 1989. Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group. In S.P. Reidel & P.R. Hooper (eds), *Volcanism and Tectonism in the Columbia River Flood-Basalt Province, Geol. Soc. Am. Spec. Pap.* 239:1–20.

Turcotte, D.L. & G. Schubert 1982. *Geodynamics: Application of Continuum Physics to Geological Problems.* New York:Wiley, 450 pp.

Tutuncu, A.N., A.L. Podio & M.M. Sharma 1994. An experimental investigation of factors influencing compressional- and shear-wave velocities and attenuations in tight gas sandstones. *Geophysics* 59:77–86.

Watters, T.R. 1989. Periodically spaced anticlines of the Columbia Plateau. In S.P. Reidel & P.R. Hooper (eds), *Volcanism and Tectonism in the Columbia River Flood-Basalt Province, Geol. Soc. Am. Spec. Pap.* 239:283–292.

Watters, T.R. 1991. Origin of periodically spaced wrinkle ridges on the Tharsis Plateau of Mars. *J. Geophys. Res.* 96:15,599–15,616.

Zoback, M.L. & M.D. Zoback 1980. State of stress in the conterminous United States. *J. Geophys. Res.* 85:6113–6156.

Zuber, M.T. & L.L. Aist 1990. The shallow structure of the Martian lithosphere in the vicinity of the ridged plains. *J. Geophys. Res.* 95:14,215–14,230.