Geological Society of America
Special Paper 239
1989

Periodically spaced anticlines of the Columbia Plateau

Thomas R. Watters
Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, D.C. 20560

ABSTRACT

Deformation of the continental flood-basalt in the westernmost portion of the Columbia Plateau has resulted in regularly spaced anticlinal ridges. The periodic nature of the anticlines is characterized by dividing the Yakima fold belt into three domains on the basis of spacings and orientations: (1) the northern domain, made up of the eastern segments of Umtanum Ridge, the Saddle Mountains, and the Frenchman Hills; (2) the central domain, made up of segments of Rattlesnake Ridge, the eastern segments of Horse Heaven Hills, Yakima Ridge, the western segments of Umtanum Ridge, Cleman Mountain, Bethel Ridge, and Manastash Ridge; and (3) the southern domain, made up of Gordon Ridge, the Columbia Hills, the western segment of Horse Heaven Hills, Toppenish Ridge, and Ahtanum Ridge. The northern, central, and southern domains have mean spacings of 19.6, 11.6, and 27.6 km, respectively, with a total range of 4 to 36 km and a mean of 20.4 km (n = 203). The basalts are modeled as a multilayer of thin linear elastic plates with frictionless contacts, resting on a mechanically weak elastic substrate of finite thickness, that has buckled at a critical wavelength of folding. Free slip between layers is assumed, based on the presence of thin sedimentary interbeds in the Grande Ronde Basalt separating groups of flows with an average thickness of roughly 280 m. Many of the observed spacings can be explained by this model, given that: (1) the ratio in Young's modulus between the basalt and underlying sediments $E/E_0 \geqslant 1{,}000$, (2) the thickness of the Grande Ronde Basalt was between 1,200 and 2,300 m when the present wavelengths were established, and (3) the average thickness of a layer in the multilayer is between 200 and 400 m. The lack of well-developed anticline-syncline pairs in the shape of a sinusoid may be the result of plastic yielding in the cores of the anticlines after initial deformation of the basalts into low amplitude folds. Elastic buckling coupled with plastic yielding confined to the hinge area could account for the asymmetric fold geometry of many of the anticlines.

INTRODUCTION

The Miocene continental flood-basalts of the Columbia Plateau in the northwestern United States have been deformed into a series of anticlinal ridges. The anticlines (or Yakima folds) are generally asymmetric in cross section, and ridge segments commonly occur in en echelon arrangements. The Yakima folds have been interpreted to be the result of one of the following: (1) drape folding generated by vertical movement of narrow basement blocks on high-angle reverse faults (Bentley, 1977); (2) fault ramp flexure with a décollement near the base of the basalts (Bruhn, 1981); (3) drag folding on interbasalt and sub-basalt detachments (Campbell and Bentley, 1981; Bentley, 1982); (4) buckling over shallow detachments in the basalt sequence followed by reverse to thrust faulting of the folds (Price, 1982); (5) buckling of the entire basalt sequence simultaneously, with the emplacement of the oldest flows followed by dominantly reverse to thrust faulting (Reidel, 1984); or (6) initial buckling in response to a horizontal compressive load coupled with a layer instability between the basalts and sub-basalt rock (Watters, 1988). An important characteristic of the anticlinal ridges of the Columbia Plateau is their apparent periodic spacing. The spacing of the ridges varies throughout the fold belt, but is consistent within certain domains.

The purpose of this investigation is to characterize periodic

Watters, T. R., 1989, Periodically spaced anticlines of the Columbia Plateau, *in* Reidel, S. P., and Hooper, P. R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Boulder, Colorado, Geological Society of America, Special Paper 239.

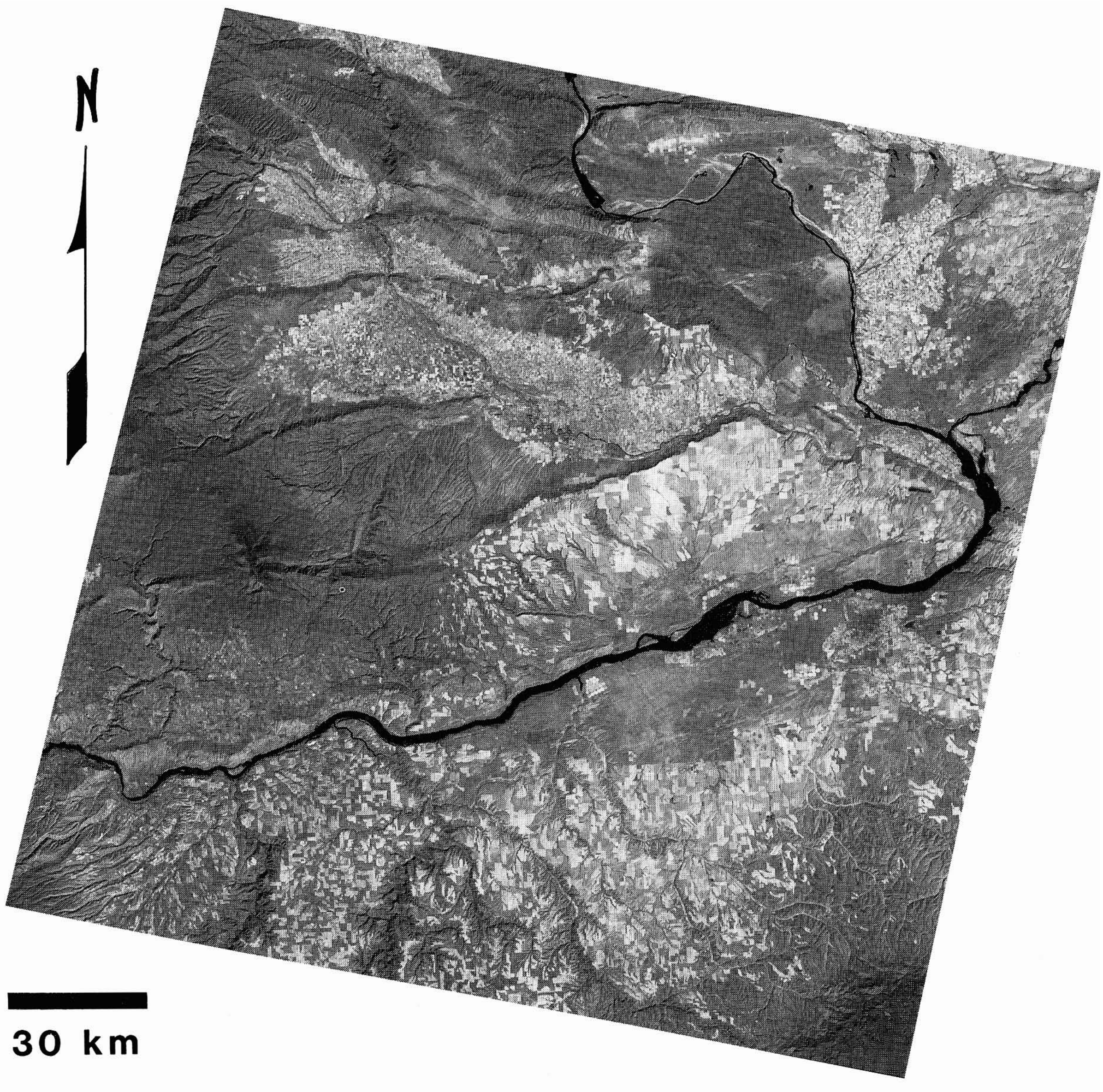

Figure 1. Portion of the Yakima fold belt on the Columbia Plateau. The Yakima folds trend roughly east-west and are bounded by the Cascade Range to the west. Many of the anticlines are asymmetric and north vergent with gently sloping southern limbs. The Columbia River dissects the Saddle Mountains ridge (top of image) and flanks the Columbia Hills ridge (bottom of image) (Landsat 4, scene ID# 4009518173).

spacing of the anticlinal ridges. The Yakima fold belt is divided into distinct domains on the basis of spacing and orientation of the anticlines. Assuming the basalts behave like a series of elastic plates, a buckling model is introduced in an effort to account for the periodic nature of the anticlines. The critical stress at which the buckling instability develops is shown to be within the yield-strength envelope of the basalts determined using Byerlee's law.

TECTONIC SETTING

The continental flood-basalts of the Columbia Plateau, located on the western margin of the North American plate, cover an area on the order of 164,000 km^2 (Tolan and others, this volume). Although compressional deformation of the basalts has resulted in local uplift, the region has experienced general subsidence (Reidel and others, this volume) and thus, may be more appropriately termed the Columbia Basin (Campbell, this volume; Anderson, 1987).

The ridges of the Yakima fold belt, as seen through remote sensing, are narrow, sinuous, and asymmetric (Fig. 1). These anticlines generally trend east-west and are separated by broad, flat-bottomed synclines. The cross-sectional geometry of the anticlines varies from asymmetric to rectangular (box fold) (Reidel, 1984; Watters, 1988; Anderson, 1987; Reidel and others, this volume). Many of the asymmetric anticlines are north vergent with a gently dipping southern limb (Fig. 2), but in some ridges this geometry reverses from one segment to the next or may change along strike within a given segment. Strike-slip faults often separate ridge segments of opposite fold geometry (Reidel, 1978; Fecht, 1978; Bentley and others, 1980; Reidel, 1984; Anderson, 1987). Reverse to thrust faults are associated with the steeply dipping vergent side of the asymmetric ridges, and segments with box fold geometries may have thrust faults associated with the back limb (back thrust) as well (see Campbell and Bentley, 1981).

The Yakima folds die out in the Palouse subprovince (Fig. 1) to the east. To the west the anticlines appear to be bounded by the Cascade Range (Fig. 1). Campbell (this volume) notes that the anticlines in the north and central portions of the fold belt either become broad flexures near the margin or die out completely. In the southwestern portion of the plateau, however, Anderson (1987) and Beeson and others (this volume) report that Yakima fold belt structures occur in Columbia River basalts within the Cascade Range.

The origin of the stresses acting on the Columbia Plateau is attributed to plate action in the Pacific Northwest. The clockwise rotation evident in paleomagnetic studies of the Coast Range and western and central Washington (see Reidel and others, 1984) is related to right-lateral shear between the North American and oceanic plates (Beck, 1980). Reidel and others (1984) suggest that the stresses resulting from oblique subduction at the convergent plate margin result in compressional-shear deformation on the plateau and elsewhere in the western United States. Their data support rotation through a localized dextral shear rather than rigid block or microplate rotation.

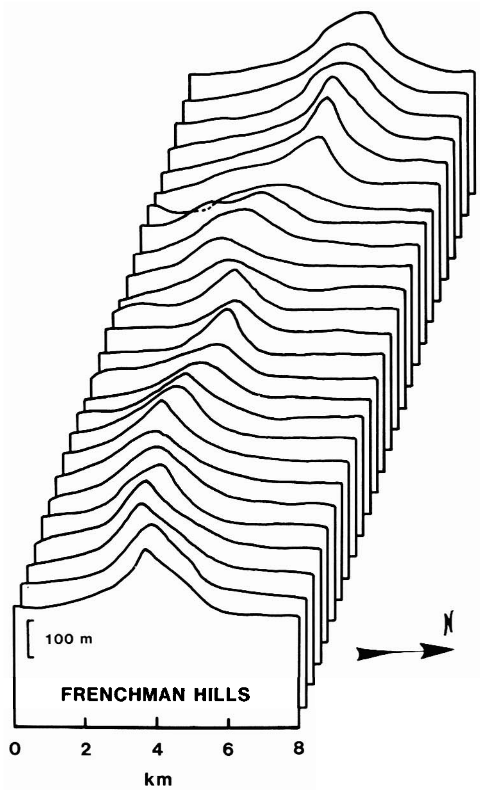

Figure 2. Topographic profiles of a portion of the Frenchman Hills anticline. Cross sections are spaced at 1-km intervals with a roughly 10× vertical exaggeration. Measurements were made from the Priest Rapids Quadrangle, U.S. Geological Survey, topographic map, 1:100,000.

PERIODIC SPACING

The periodic nature of the anticlinal ridges in the Yakima fold belt has been noted in a number of studies (Bentley, 1982; Watters and Maxwell, 1985; Anderson and others, 1987). The exception to the roughly east-west trends of the anticlines occurs in the eastern portion of the fold belt where segments of the Horse Heaven Hills and Rattlesnake Ridge are deflected along the northwest-southeast trend of the Cle Elum–Wallula deformed zone (CLEW; Fig. 3; see Campbell, this volume).

The Yakima fold belt can be subdivided into three domains on the basis of spacing and orientation of the anticlinal ridges. The spacing of the anticlines was measured from a tectonic map of the Columbia Plateau (Tolan and Crowley, 1986) using a series of sampling traverses spaced at roughly 3-km intervals oriented perpendicular to the predominant trend of the folds in the domain. Ridge segments with roughly uniform trends were digitized in the three domains, and mean orientations determined using the double angle method (see Davis, 1986).

The northern domain of the Yakima fold belt is made up of the eastern segments of Umtanum Ridge, the Saddle Mountains, and the Frenchman Hills (Fig. 3). In this domain the mean direction of the anticlines is N79.8°W (Fig. 4A-1; Table 1), and the mean spacing is 19.6 km (Fig 4B-1; Table 2). The central domain is made up of segments of Rattlesnake Ridge (part of the CLEW), eastern segments of the Horse Heaven Hills, Yakima Ridge, western segments of Umtanum Ridge, Cleman Mountain, Bethel Ridge, and Manastash Ridge. The spacing and orientation of the anticlines in this domain is the most variable. The mean direction of ridges is N71°W (Fig. 4A-2; Table 1) and the mean spacing is 11.6 km (Fig. 4B-2; Table 2). The southern domain is made up of Gordon Ridge, Columbia Hills, western segments of Horse Heaven Hills, Toppenish Ridge, and Ahtanum Ridge (Fig. 3). The mean direction of the anticlines in this domain is N79.1°E (Fig. 4A-3; Table 1), and the mean spacing is 27.6 km (Fig. 4B-3; Table 2).

The range in ridge spacing across all three domains is 4 to 36 km with a mean of 20.4 km ($n = 203$). It is of interest to note that the central domain, containing the CLEW structures, has the greatest range in spacing (27 km) and the smallest mean spacing, and divides the fold belt.

ANALYSIS OF SPACING

The periodic spacing of the anticlines in the Yakima fold belt suggests that the basalts have buckled at a dominant or

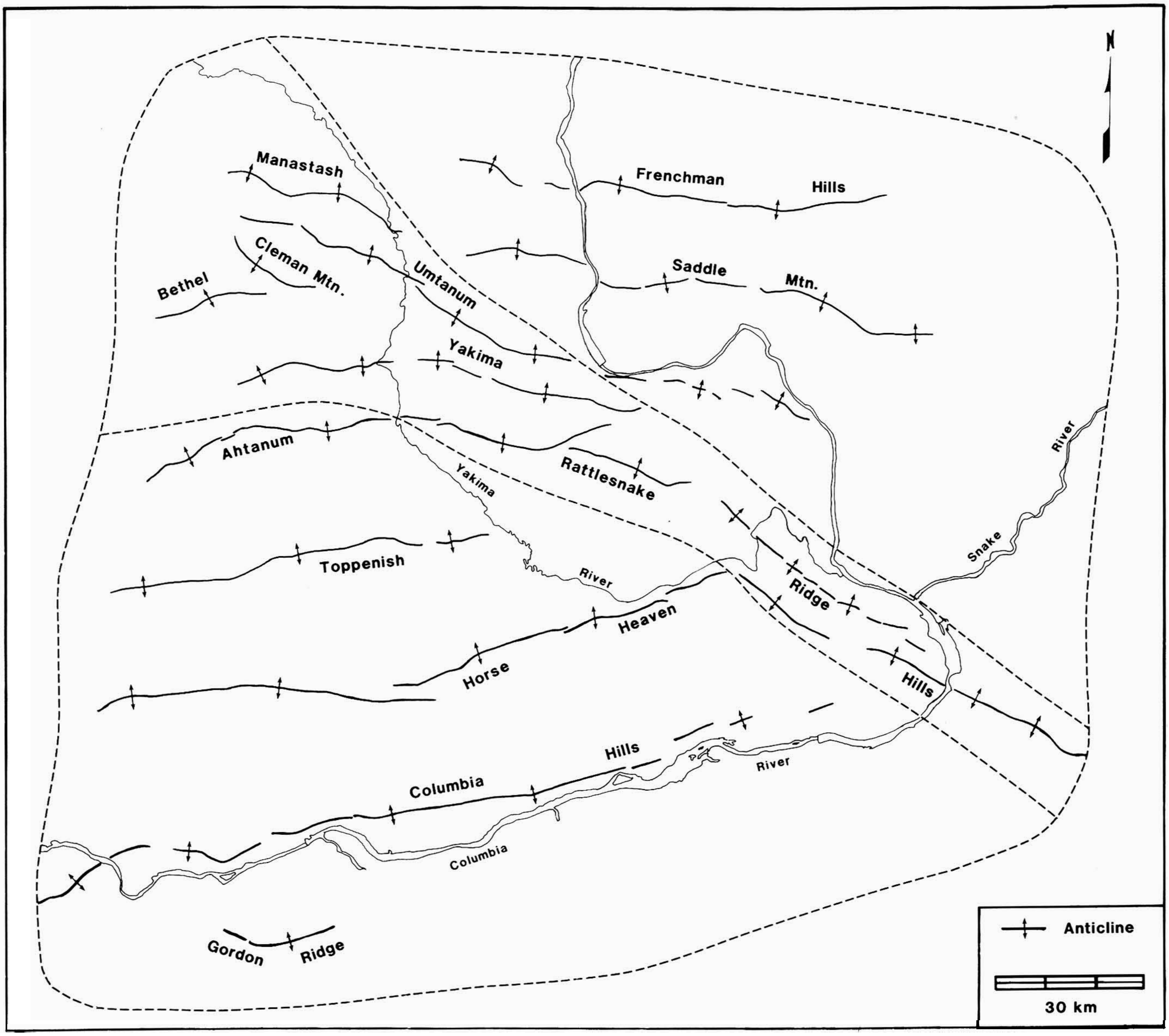

Figure 3. Anticlinal ridges of the Yakima fold belt. The fold belt was divided into three domains on the basis of orientations and spacings of the anticlines. The southern domain contains Gordon Ridge, the Columbia Hills, western segments of the Horse Heaven Hills, Toppenish Ridge, and Ahtanum Ridge. The central domain is made up of eastern segments of the Horse Heaven Hills, Rattlesnake Ridge, Yakima Ridge, western segments of Umtanum Ridge, the Cleman Mountains, Bethel Ridge, and Manastash Ridge. The northern domain contains eastern segments of Umtanum Ridge, the Saddle Mountains, and the Frenchman Hills.

critical wavelength. Such a deformation mechanism requires that a significant strength contrast exist between the basalts and sub-basalt rocks and that the thickness of the two units is constrained.

The rocks underlying a large portion of the Columbia River basalts consist of a sequence of Jurassic to early Miocene volcaniclastic and fluvial sediments ranging in thickness from 1,000 to 7,000 m (Campbell, this volume). These sediments are generally poorly consolidated (N. Campbell, personal communication) and probably rest on granitic basement (Campbell, this volume). At least 3,000 m of sediments underlies most of the anticlines, with a rapid decrease in thickness to the north, south, and east of the Yakima fold belt (see Fig. 6 in Campbell, this volume). In the Palouse subprovince to the east of the fold belt where the anticlines are not present, the sediments thin and the basalt overlies crystalline basement (Reidel, 1984; Reidel and others, this volume).

The thickness of the Columbia River Basalt Group is at a maximum of about 4,000 m near the Pasco Basin (Reidel and

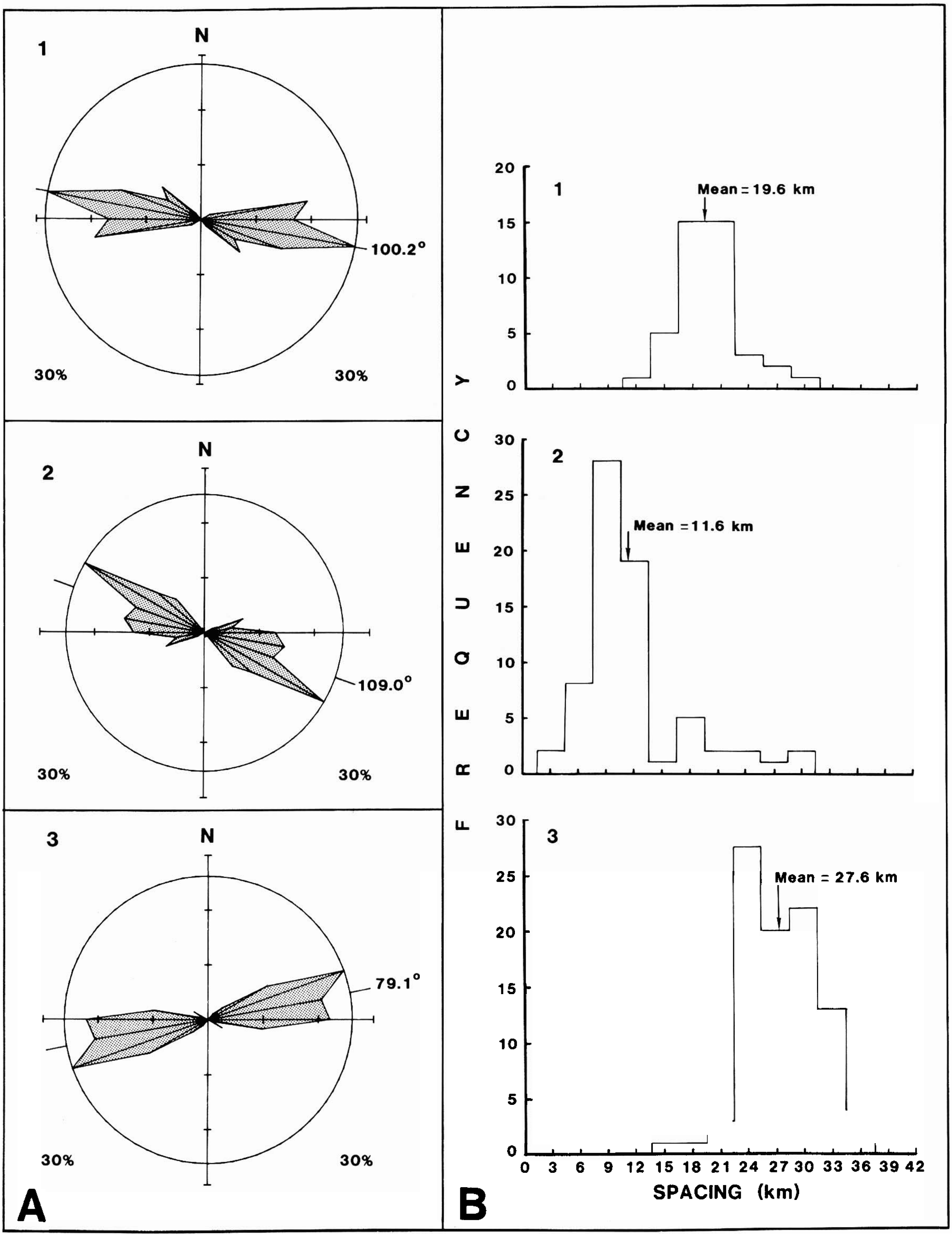

Figure 4. Rose diagrams of orientations and histograms of spacings of anticlines in the three domains of the Yakima fold belt. (A) Mean directions in the northern (1), central (2), and southern (3) domains are 100.2° (N79.8°W), 109.0° (N71°W), and 79.1° (N79.1°E), respectively. Orientations of the ridge segments are plotted in 10° bins. Additional statistics are given in Table 1. (B) Mean spacings in the northern (1), central (2), and southern (3) domains are 19.6 (*n* = 42), 11.6 (*n* = 70), and 27.6 km (*n* = 91), respectively. Additional statistics are given in Table 2.

TABLE 1. ORIENTATION OF ANTICLINES IN THE YAKIMA FOLD BELT

DOMAIN	$\overline{\theta}$	s_o^2	n
Northern	100.2°	0.18	30
Central	109.0°	0.24	64
Southern	79.1°	0.14	67

$\overline{\theta}$ = mean direction, s_o^2 = circular variance, and n = number of observations. The mean direction was determined using the double angle method for oriented data (Davis, 1986). The circular variance is a measure of dispersion, with the greatest scatter at s_o^2 = 1.0.

TABLE 2. SPACINGS OF ANTICLINES IN THE YAKIMA FOLD BELT

DOMAIN	$\overline{x}$, km	s, km	x_{MAX}-x_{min}, km	n
Northern	19.63	3.48	28.93 - 13.42	42
Central	11.61	5.55	31.17 - 4.06	70
Southern	27.55	4.14	36.11 - 15.87	91

$\overline{x}$ = mean spacings, s = standard deviation, range = x_{max}-x_{min}, and n = number of observations. Spacings were determined using a series of sampling traverses spaced at approximately 3-km intervals oriented perpendicular to the predominant trend of the anticlines in each domain.

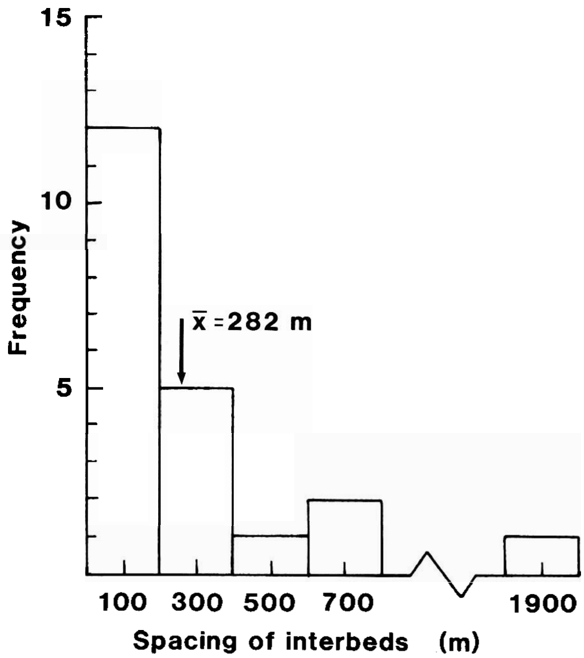

Figure 5. Histogram of spacing of sedimentary interbeds in the Grande Ronde Basalt. Spacing ranges from approximately 20 to 1,800 m with a mean of 282 m (n = 21). Data from Reidel and others, this volume.

others, 1982; Reidel and others, this volume; Campbell, this volume). Evidence of thinning and pinching out of flows over and on a number of the anticlines in the fold belt suggests that the initiation of buckling followed shortly after the emplacement of the oldest basalt flows (the Grande Ronde), and structural relief on the folds was buried by younger flows (Reidel, 1984; Anderson, 1987; Reidel and others, this volume). Thus, the dominant wavelengths observed in the domains of the fold belt were probably established in Grande Ronde time when the thickness of the basalts was some fraction of the present total. The total thickness of the Grande Ronde Basalt in the area of the fold belt is between roughly 1,000 and 3,500 m (see Fig. 3 in Reidel and others, this volume); thus, the thickness at the time the present wavelengths were established is estimated to be within this range.

Recent well-log data from three deep wells located within the Yakima fold belt show evidence of thin sedimentary interbeds in the Grande Ronde Basalt (Reidel and others, this volume). These interbeds separate individual flows and groups of flows ranging in thickness from roughly 20 to 1,800 m with a mean of about 280 m (Fig. 5; see Fig. 5 in Reidel and others, this volume). The occurrence of interbeds in the Grande Ronde Basalt is much less frequent north and south of the fold belt (S. Reidel, personal communication, 1988), suggesting a relationship between the interbeds and the location of the Yakima folds. The presence of mechanically weak interbeds is important in the formulation of a buckling model because it may be assumed that they allow some degree of slip between groups of flows (see Biot, 1961; Currie and others, 1962; Johnson, 1984). Thus, the basalts may be modeled as a multilayer with free slip between groups of flows with an average thickness of about 280 m.

A linear elastic rheology is chosen to approximate the behavior of the basalts and underlying sediments. This choice is justified because deformation has occurred at the free surface in the brittle domain under little or no confining pressure and low temperatures. Alternative rheologies such as linearly viscous or power-law flow require ductile behavior. In the context of rock mechanics, few rocks exhibit ductility at low pressures and temperatures (Jaeger and Cook, 1979, p. 228). Further, there is no field evidence of true ductile behavior in the deformed Columbia River basalts.

In this model, it is assumed that the basalts behave as a series of thin, linear elastic plates with essentially frictionless contacts resting on a mechanically weak elastic substrate of finite thickness, which is in turn resting on a rigid boundary (Fig. 6). The deflection of an elastic plate in infinitesimal strain resting on a substrate at the free surface subjected to an in-plane horizontal end load is given by:

$$D\frac{d^4w}{dx^4} + P\frac{d^2w}{dx^2} = 0$$

where w is the deflection and P is the horizontal force. The flexural rigidity D is related to the thickness of the elastic plate h by:

$$D = \frac{Eh^3}{12(1-\nu^2)} \tag{2}$$

where E is Young's modulus and ν is Poisson's ratio (see Turcotte and Schubert, 1982; McAdoo and Sandwell, 1985). Since the plate is a multilayer, $h = nt$, where n is the number of layers and t is the average thickness of a layer. The resistance of the substrate to bending is given by k in equation 1. In this case the total resistance consists of two components: (1) the elastic resistance of the substrate and (2) the hydrostatic restoring force that incorporates the influence of gravity (i.e., body forces). The restoring force that results from the replacement of substrate material in a vertical column by less dense material (in the case of deformation at the free surface, atmosphere) is given by:

$$(\rho_0 - \rho_A)g \tag{3}$$

where ρ_0 and ρ_A are the density of the substrate and atmosphere, respectively, and g is the acceleration due to gravity (see Turcotte and Schubert, 1982). Because ρ_A is negligible, the expression for the restoring force (equation 3) can be reduced to $\rho_0 g$.

The thickness of the substrate is important in determining the elastic resistance to bending. Johnson (1984) has shown that in order for a medium of finite thickness to approximate one of infinite thickness, the ratio of thickness of the substrate to the wavelength of folding must be greater than 0.6 (also see Currie and others, 1962). This is not the case for the Yakima folds. The elastic resistance of a substrate of finite thickness can be approximated by assuming that the medium consists of a series of independent elastic columns, each with a Young's modulus of E_0 (Currie and others, 1962; Johnson, 1984). The force per unit length necessary to strain each column is given by E_0/h_0 where h_0 is the thickness of the substrate. Thus, the total resistance to bending is given by:

$$k = \frac{E_0}{h_0} + \rho_0 g \tag{4}$$

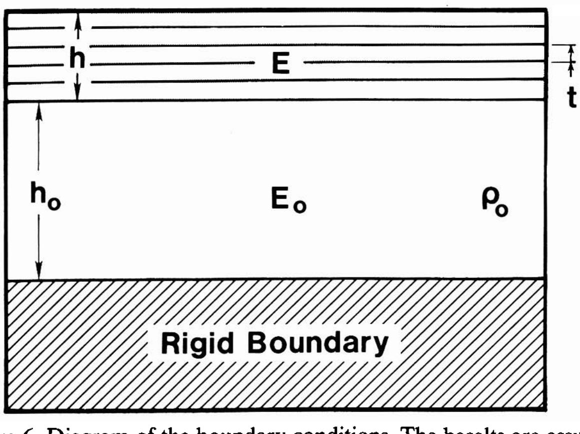

Figure 6. Diagram of the boundary conditions. The basalts are assumed to behave as a multilayer of elastic plates with Young's modulus E resting on a mechanically weak substrate with Young's modulus E_o and density ρ_0. Frictionless contacts are assumed between the individual layers of thickness t. The substrate is of finite thickness h_o and is resting on a strong rigid boundary.

The differential equation for the deflection of an elastic plate (equation 1) has been solved for a number of relevant boundary conditions (Hetenyi, 1949; Turcotte and Schubert, 1982; Johnson, 1984). It can be shown that a sinusoidal deflection of the plate in the form:

$$w = C \sin(ax) \tag{5}$$

where C is a constant and a is the length scale, satisfies equation 1. When the end load reaches the elastic buckling limit P_o, the critical wavelength developed is given by:

$$\lambda_c = 2\pi \left[\left(\frac{h_o E n t^3}{12(1-\nu)^2 E_o} \right) + \left(\frac{E n t^3}{12(1-\nu^2)\rho_0 g} \right) \right]^{1/4} \tag{6}$$

(see Appendix 1). It is clear from equation 6 that the buckling wavelength is dependent on the contrast in Young's modulus between the basalts and the underlying sediments (E/E_0) and the unit weight of the sediments ($\rho_0 g$).

The Young's modulus of different rocks does not range beyond one or two orders of magnitude in spite of great variation in composition, grain size, and fabric (see Birch, 1966; Hatheway and Kiersch, 1982; Christensen, 1982). However, a large contrast in Young's modulus does exist between rock and unconsolidated sediments or soils. The Young's modulus of a number of different soil types is shown in Table 3. Given the Young's modulus of basalt (Table 4), contrasts as large as four orders of magnitude are possible. For example, if the sub-basalt sediments are akin to a dense sand (Table 3), then an E/E_0 of roughly 800 to 1,400 may exist. Compaction due to gravitational loading will increase the mechanical strength or rigidity of dry, granular materials [Talwani and others, 1973]. However, the role of pore-fluid pressure must be considered. High pore-fluid pressure resulting from both gravitational and tectonic loading of water-saturated sediments (Hubbert and Rubey, 1959) will offset an increase in the rigidity due to compaction. Thus, a relatively high E/E_0 is possible. Given the values of the parameters shown in Table 4, wavelength as a function of thickness of the Grande Ronde Basalt for an E/E_0 of 1,000 and 5,000 and an average thickness of individual units in the multilayer t of 200 to 400 m are shown in Figure 7.

The strength of the material is an important consideration in determining the validity of a model based on elastic instability theory. In the upper crust, rock strength is controlled by the frictional resistance of brittle failure by sliding on randomly oriented fractures or joints (Brace and Kohlstedt, 1980; Vink and others, 1984). The frictional resistance and, thus, the maximum strength can be directly related to the normal and shear stresses by Byerlee's law:

$$\begin{aligned} \sigma_1 &\simeq 5\sigma_3, & \sigma_3 &< 110 \text{ MPa} \\ \sigma_1 &\simeq 3.1\sigma_3 + 210, & \sigma_3 &> 110 \text{ MPa} \end{aligned} \tag{7}$$

expressed here in terms of the maximum (σ_1) and minimum (σ_3)

TABLE 3. YOUNG'S MODULUS FOR A VARIETY OF DIFFERENT SOIL TYPES

MATERIAL	E,Pa
Hard clay	6.895×10^6 - 1.724×10^7
Sandy clay	2.758×10^7 - 4.137×10^7
Silty sand	6.895×10^6 - 2.069×10^7
Loose sand	1.034×10^7 - 2.413×10^7
Dense sand	4.827×10^7 - 8.274×10^7
Dense sand and gravel	9.653×10^7 - 1.931×10^8

The values of Young's modulus E shown above are from Kézai and Mice (1975).

TABLE 4. PARAMETERS FOR MODEL

PARAMETER	DEFINITION	VALUE
h_o	thickness of substrate	3,000 m
ρ_o	density of sediments	2,000 kg m^{-3}
E	Young's modulus (basalt)	6.5×10^{10} Pa
υ	Poisson's ratio (basalt)	0.25
g	acceleration of gravity	9.8 m s^{-2}

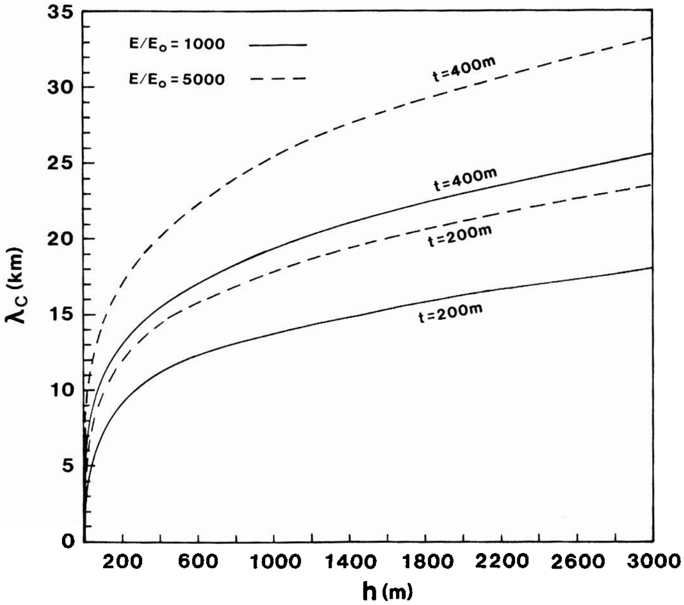

Figure 7. The critical wavelength of buckling λ_c as a function of thickness h for ratios in Young's modulus between the surface layers and substrate E/E_o = 1,000 (solid lines) and E/E_o = 5,000 (dashed lines), and thicknesses of the individual layers t = 200 and t = 400 m.

principal effective stresses (after Brace and Kohlstedt, 1980). The critical stress σ_c to achieve buckling is given by:

$$\sigma_c = \left[\left(\frac{tEE_o}{3(1-\nu^2)h_o n}\right) + \left(\frac{tE\rho_o g}{3(1-\nu^2)n}\right)\right]^{1/2} \quad (8)$$

(see Appendix 1). The critical stress as a function of thickness of the Grande Ronde Basalt for the wavelengths indicated in Figure 7 is shown in Figure 8 along with the maximum compressive strength envelope of a rock with a mean density equal to that of basalt (ρ = 2,900 kg m^{-3}). At stresses above the maximum compressive strength, gross fracturing in the form of reverse or thrust faulting is favored over buckling. Thus, given the model parameters, admissable wavelengths can be obtained for a range of minimum thicknesses of the Grande Ronde Basalt. With an E/E_0 of 1,000, the minimum thickness ranges from roughly 1,400 to 2,300 m (Fig. 8), corresponding to wavelengths of roughly 15 to 24 km (Fig. 7). With an E/E_0 of 5,000 the minimum thickness ranges from 1,200 to 1,900 m, corresponding to wavelengths of roughly 19 to 30 km. The expected wavelengths agree well with those observed in the northern and southern domains and to a lesser degree with those observed in the central domain (see Table 2). As mentioned previously, the central domain contains the "CLEW structures" and is a zone of more intense horizontal shortening in the fold belt (Bentley, 1982). The anomalous spacing of the domain may be due to the influence of pre-basalt structures related to the Olympic-Wallowa deformed zone (Campbell, this volume), a topographic feature along the trend of the CLEW extending across the Cascade Range.

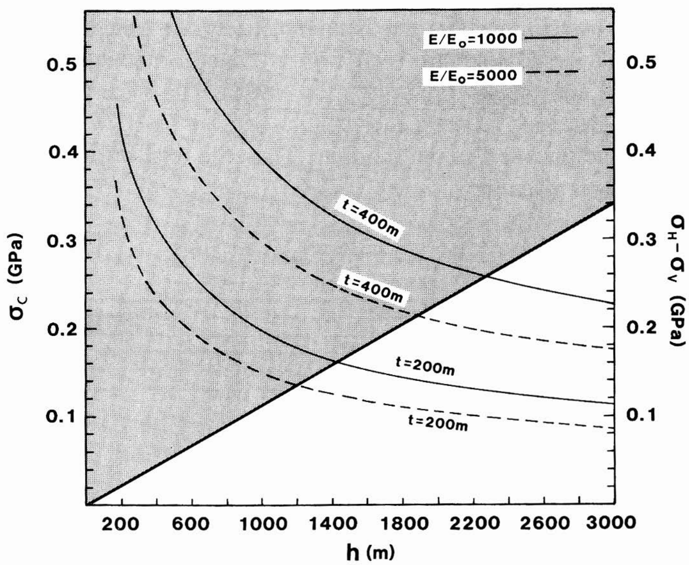

Figure 8. The critical stress σ_c to achieve buckling as a function of thickness h for ratios in Young's modulus between the surface layers and substrate E/E_o = 1,000 (solid lines) and E/E_o = 5,000 (dashed lines), and thicknesses of the individual layers t = 200 and t = 400 m. The difference between the maximum horizontal and vertical stress is plotted as a function of depth. The double-width solid line represents the maximum compressive strength of a basalt (ρ = 2,900 kg m^{-3}) sequence on the surface assuming no pore fluid pressure (dry rock). Critical stresses that fall above this line, in the shaded zone, exceed the maximum compressive strength of the basalt, and gross fracturing is expected over buckling.

DISCUSSION

Equation 5 predicts a sinusoidal deflection of the buckling multilayer (i.e., anticlines and synclines of equal amplitude). The narrow anticlines and broad synclines of the Yakima fold belt are not a good approximation to a sine wave (see Anderson, 1987). The asymmetric anticlines are characterized by a narrow crestal hinge separating a long, straight, gently dipping limb. This geometry is similar to that of a kink fold (see Anderson, 1987; Price and Watkinson, this volume; Price, 1982).

Much of the strain manifest in the Yakima folds, excluding displacements on associated reverse to thrust faults (see Watters, 1988), has been accomplished through cataclastic flow on layer-internal faults (Price, 1982). Cataclastic behavior may be thought of as a form of yielding that occurs in discrete locations where the stress exceeds the yield strength. Yielding in this form is most easily approximated by plastic behavior. If the basalts are assumed to behave like an elastic-plastic material in finite strain, and if the yield strength is low relative to the elastic modulus ($E/1$-ν^2), the basalts would not be expected to bend very much before yielding (see Johnson, 1984). With initial elastic buckling in the form of low-amplitude folds, plastic yielding may occur in the cores of the anticlines where bending stresses are high (see Currie and others, 1962), propagating in the direction of the free surface. This might serve to localize the amplification of the folds in the areas of the anticlines, resulting in structures with narrow crestal hinges and straight limbs. Such a mechanism would involve rapid closing of the folds, and with continued horizontal shortening, the development of reverse to thrust faulting (see Watters, 1988). Thus, elastic buckling followed by localized plastic yielding and the eventual development of reverse to thrust faulting may explain the periodic spacing and fold geometry of many of the anticlinal ridges of the Yakima fold belt.

SUMMARY

The Columbia River basalts of the western Columbia Plateau have been deformed into periodically spaced anticlinal ridges. The anticlines are narrow, asymmetric to rectangular in cross section, and separated by broad, relatively undeformed synclines. The origin of the stresses that deformed the basalts in the Yakima fold belt is attributed to plate action in the Pacific Northwest. The Yakima fold belt can be divided into three domains on the basis of spacing and orientation of the anticlines. In the northern domain, the eastern segments of the Umtanum Ridge, the Saddle Mountains, and the Frenchman Hills have a mean direction of N79.8°W and a mean spacing of 19.6 km. The anticlines of the central domain, made up of segments of Rattlesnake Ridge, eastern segments of the Horse Heaven Hills, Yakima Ridge, and western segments of Umtanum Ridge and Manastash Ridge, have a mean direction of N71°W and a mean spacing of 11.6 km. In the southern domain, Gordon Ridge, Columbia Hills, western segments of the Horse Heaven Hills, Toppenish Ridge, and Ahtanum Ridge have a mean direction of N79.1°E and a mean spacing of 27.6 km. The mean spacing across all three domains is 20.4 km (n = 203).

A model for the basalts involving a series of thin, linear elastic plates with frictionless contacts resting on a mechanically weak elastic substrate of finite thickness is proposed. Many of the observed spacings in the three domains can be explained given the model parameters and (1) a ratio of Young's modulus between the basalt and underlying sediments $E/E_0 \geqslant 1{,}000$, (2) the average layer thickness t between 200 and 400 m, and (3) a thickness of the Grande Ronde Basalt of between 1,200 and 2,300 m when the presently observed wavelengths were established.

The absence of anticlines and synclines of equal amplitude predicted by the model may be the result of plastic yielding in the form of cataclastic flow in the cores of the anticlines after the initial elastic deflection of the basalts into low-amplitude folds (in infinitesimal strain). Plastic yielding (in finite strain) concentrated in the hinge area of the anticlines could (1) account for the asymmetric fold geometry and (2) result in rapid closing of the fold and development of reverse to thrust faulting.

ACKNOWLEDGMENTS

I am indebted to Sean Solomon, Steve Reidel and David McAdoo for their reviews and valuable discussions and comments on the fold model. I thank Jim Anderson and Maria Zuber for their reviews of an early version of the manuscript. I also thank Michael Tuttle and John Chadwick for their assistance in data collection and in preparing the figures, Donna Slattery for typing the manuscript and Priscilla Strain for editing the text. This research was supported by NASA grants NAGW-940 and NAGW-1106.

APPENDIX 1. DERIVATION OF EQUATIONS 6 AND 8.

The equation for the deflection of the plate

$$D\frac{d^4w}{dx^4} + P\frac{d^2w}{dx^2} + kw = 0 \tag{A-1}$$

is satisfied by a sinusoidal deflection given by equation (5)

$$w = C\sin(ax)$$

where C is a constant and a=$2\pi/\lambda$. Substituting equation 5 into equation A-1 and dividing through by $C\sin(2\pi/\lambda)x$ yields

$$Da^4 - Pa^2 + k = 0 \tag{A-2}$$

where

$$a^2 = \frac{P\pm(P^2-4Dk)^{1/2}}{2D} \tag{A-3}$$

Since $a=2\pi/\lambda$, equation A-3 can be written as

$$\left(\frac{2\pi}{\lambda}\right)^2 = \frac{P \pm (P^2-4DK)^{1/2}}{2D} \quad \text{(A-4)}$$

In order for the wavelength λ to be real the applied load must reach a critical value P_c defined by setting the term under the radical in equation A-4 to zero. Thus

$$P_c = (4Dk)^{1/2} \quad \text{(A-5)}$$

Then equation A-4 reduces to

$$\left(\frac{2\pi}{\lambda}\right)^2 = \frac{P}{2D} \quad \text{(A-6)}$$

Substituting P_c for P in equation A-6 the critical wavelength is given by

$$\lambda_c = 2\pi\left(\frac{D}{k}\right)^{1/4} \quad \text{(A-7)}$$

Substituting equation 2 where $h=nt$ and equation 4 into equation A-7 yields

$$\lambda_c = 2\pi\left[\left(\frac{h_o Ent^3}{12(1-\nu^2)E_o}\right) + \left(\frac{Ent^3}{12(1-\nu^2)\rho_o g}\right)\right]^{1/4}$$

The expression for the critical stress is obtained by substituting equation 2 and equation 4 into equation A-6 and replacing P_c with $\sigma_c nt$ yielding

$$\sigma_c = \left[\left(\frac{tEE_o}{3(1-\nu^2)h_o n}\right) + \left(\frac{tE\rho_o g}{3(1-\nu^2)n}\right)\right]^{1/2}$$

REFERENCES CITED

Anderson, J. L., 1987, Structural geology and ages of deformation of a portion of the southwest Columbia Plateau, Washington and Oregon [Ph.D. thesis]: Los Angeles, University of Southern California, 283 p.

Anderson, J. L., Beeson, M. H., and Tolan, T. L., 1987, Tectonic evolution of the southwest Columbia Plateau: Geological Society of America Abstracts with Programs, v. 19, p. 354.

Beck, M. E., Jr., 1980, Paleomagnetic record of plate-margin tectonic processes along the western edge of North America: Journal of Geophysical Research, v. 81, p. 7115–7131.

Bentley, R. D., 1977, Stratigraphy of the Yakima basalts and structural evolution of the Yakima Ridges in the western Columbia Plateau, *in* Brown, E. H., and Ellis, R. C., eds., Geology excursions in the Pacific Northwest: Bellingham, Western Washington University, p. 339–389.

——, 1982, Later Tertiary thin skin deformation of the Columbia River basalt in the western Columbia Plateau, Washington–Oregon: EOS Transactions of the American Geophysical Union, v. 63, p. 173.

Bentley, R. D., Anderson, J. L., Campbell, N. P., and Swanson, D. A., 1980, Stratigraphy and structure of the Yakima Reservation, with emphasis on the Columbia River Basalt Group: U.S. Geological Survey Open-File Report 80–200, 76 p.

Biot, M. A., 1961, Theory of folding of stratified viscoelastic media and its implications in tectonics and orogenesis: Geological Society of America Bulletin, v. 72, p. 1595–1620.

Birch, F., 1966, Compressibility; Elastic constants, *in* Clark, S. P., ed., Handbook of physical constants: Geological Society of America Memoir 97, p. 97–173.

Brace, W. F., and Kohlstedt, D. L., 1980, Limits on lithospheric stress imposed by laboratory experiments: Journal of Geophysical Research, v. 85, p. 6248–6252.

Bruhn, R. L., 1981, Preliminary analysis of deformation in part of the Yakima fold belt, south-central Washington: Richland, Washington, Washington Public Power Supply System Report, 27 p.

Campbell, N. P., and Bentley, R. D., 1981, Late Quaternary deformation of the Toppenish Ridge uplift in south-central Washington: Geology, v. 9, p. 519–524.

Christensen, N. I., 1982, Seismic velocities, *in* Carmichael, R. S., ed., Handbook of physical properties of rocks: Boca Raton, Florida, CRC Press, p. 1–228.

Currie, J. B., Patnode, H. W. and Trump, R. P., 1962, Development of folds in sedimentary strata: Geological Society of America Bulletin, v. 73, p. 655–674.

Davis, J. C., 1986, Statistics and data analysis in geology: New York, Wiley and Sons, 646 p.

Fecht, K. R., 1978, Geology of the Gable Mountain–Gable Butte area: Richland, Washington, Rockwell Hanford Operations Report RHO-BWI-LD-5, 70 p.

Hatheway, A. W., and Kiersch, G. A., 1982, Engineering properties of rocks, *in* Carmichael, R. S., ed., Handbook of physical properties of rocks: Boca Raton, Florida, CRC Press, p. 289–331.

Hetenyi, M., 1949, Beams on elastic foundation: Ann Arbor, University of Michigan Press, 255 p.

Hubbert, M. K., and Rubey, W. W., 1959, Role of fluid pressure in mechanics of overthrust faulting: Geological Society of America Bulletin, v. 70, p. 201–252.

Jaeger, J. C., and Cook, N.G.W., 1979, Fundamentals of rock mechanics, third edition: London, Chapman and Hall, 593 p.

Johnson, A. M., 1984, Physical processes in geology, second edition: San Francisco, California, Freeman, Cooper and Co., 577 p.

Kézdi, A., and Mice, C. E., 1975, Pile foundations, *in* Winterkorn, H. F., and Fang, H., eds., Foundation engineering handbook: New York, Van Nostrand Reinhold, p. 556–600.

McAdoo, D. C., and Sandwell, D. T., 1985, Folding of oceanic lithosphere: Journal of Geophysical Research, v. 90, p. 8563–8569.

Price, E. H., 1982, Structural geometry, strain distribution, and tectonic evolution of Umtanum Ridge at Priest Rapids, and a comparison with other selected localities within the Yakima fold structures, south-central Washington [Ph.D. thesis]: Pullman, Washington State University, 197 p.

Reidel, S. P., 1978, Stratigraphy and petrogenesis of the Grande Ronde Basalt in the lower Salmon and adjacent Snake River canyons: Richland, Washington, Rockwell Hanford Operations Report RHO–SA–62, 75 p.

——, 1984, The Saddle Mountains; The evolution of an anticline in the Yakima fold belt: American Journal of Science, v. 284, p. 942–978.

Reidel, S. P., Fecht, K. R., and Cross, R. W., 1982, Constraints on tectonic models for the Columbia Plateau from the age and growth rates of Yakima folds, *in* Proceedings of the 33rd Alaska Science Conference, Arctic Division: American Association for Advancement of Science, p. 131.

Reidel, S. P., Scott, G. R., Bazard, D. R., Cross, R. W., and Dick, B., 1984, Post-12 million year clockwise rotation in the central Columbia Plateau, Washington: Tectonics, v. 3, p. 251–273.

Talwani, P., Nur, A., and Kovach, R. L., 1973, Compressional and shear wave velocities in granular materials to 2.5 kilobars: Journal of Geophysical Research, v. 78, p. 6899–6909.

Tolan, T. L., and Crowley, W. H., Jr., 1986, Tectonic map of the Columbia Plateau and adjacent areas: Richland, Washington, Rockwell Hanford Operations Structure and Tectonic Maps SD–BWI–TI–320, scale 1:500,000.

Turcotte, D. L., and Schubert, G., 1982, Geodynamics; Application of continuum physics to geological problems: New York, J. Wiley and Sons, 450 p.

Vink, G. E., Morgan, W. J., and Zhao, W. L., 1984, Preferential rifting of continents; A source of displaced terrains: Journal of Geophysical Research, v. 89, p. 10072–10076.

Watters, T. R., 1988, Wrinkle ridge assemblages on the terrestrial planets: Journal of Geophysical Research, v. 93, p. 10235–10254.

Watters, T. R., and Maxwell, T. A., 1985, Mechanisms of basalt-plains ridge formation: Reports of Planetary Geology Program, 1984, NASA Technical Memoranda TM-87563, p. 479–481.

MANUSCRIPT ACCEPTED BY THE SOCIETY JANUARY 24, 1989

Printed in U.S.A.