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ON THE STRESS SYSTEM THAT FORMED THE LARAMIDE WIND RIVER MOUNTAINS, WYOMING

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Abstract. A seismic reflection profile obtained by the Consortium for Continental Reflection Profiling [COCORP] has delineated the Wind River thrust fault which underlies the Wind River Mountains, Wyoming. This thrust fault dips at an average angle of 30° - 40° to a depth of 24 km and possibly to 36 km. In this paper we associate the approximately constant angle of dip with the Anderson theory of faulting. With an average dip angle of 35° the derived coefficient of fraction is 0.36. We consider that the Anderson theory of faulting predicts the angle of dip of activated fractures in a rock mass pervaded by fractures in random directions.

Introduction

The Wind River Mountains in Wyoming are a range 220 km long and 70 km wide. The highest peak in the range is 4267m high. The mountains are cored by Precambrian rock 2.7 b.y. old [Naylor et al., 1970]. The mountain range was formed during the Laramide orogeny and is one of a series of Laramide ranges in Wyoming. Many of these ranges are flanked by faults which at the surface are high angle reverse or low angle thrust faults. Alternative mechanisms for their formation have been discussed in the literature [see Smithson et al., 1978, for citations], in particular, whether they were formed by vertical or horizontal movements of the earth's crust. Vertical movements would be implied by the steepening at depth of the flanking faults, while flanking faults with a moderate dip would indicate compressional deformation.

To try to resolve this problem in the Wind River range, the Consortium for Continental Reflection Profiling [COCORP] has obtained a 160 km length of deep crustal seismic reflection profile across the southeastern end of these mountains [Figure 1]. The Wind River thrust underlying the southwestern edge of the mountains can be clearly traced on these profiles to depths of at least 24 km, possibly to as deep as 30-36 km. Its dip is 30° - 35° to depths of about 15 km, and 35-45° below, [Figure 2], the dip direction varying between easterly and northeasterly.

The geometry of the thrust indicates that the Wind River Mountains were formed by horizontally directed compressional forces. There is at least 21 km of crustal shortening and 13 km of vertical uplift [Smithson et al., 1979; Brewer et al., 1980].

Style of Deformation Along the Wind River Thrust

Near the surface, where Precambrian rock overthrusts sediments of the Green River basin, the thrust is a well defined planar feature with a simple reflection character. Below this, the seismic response of the thrust is more complex, perhaps due to bifurcations, and more than one fault plane may be present [Figure 2]. There may have been more than one period of movement on different strands of the thrust, and possibly pre-Laramide fault surfaces localized thrust movements. The width of the thrust zone appears to increase at depth, to possibly as much as 2-3 km.

The thrust has a very pronounced seismic character, producing high amplitude acoustic reflections. This may be due to zones of fault gouges and/or mylonites, to the combination of many minor subparallel fault planes locally causing structural "tuning" of the seismic signal, or to the juxtaposition of rock types of sufficiently high impedence contrasts [i.e., changes in rock types or densities]. Since at least 21 km of movement occurred on the fault, any or all of these mechanisms may be possible.

The COCORP seismic profiles indicate that the Wind River Range was formed primarily by the displacement on the thrust fault. Geological maps show that the range has an anticlinal structure, so that the deformation probably took place by minor initial arching which developed into major thrusting [Smithson et al., 1979].

Calculation of the Stress System

A striking feature of the Wind River thrust is its moderate angle of dip. The angle of dip

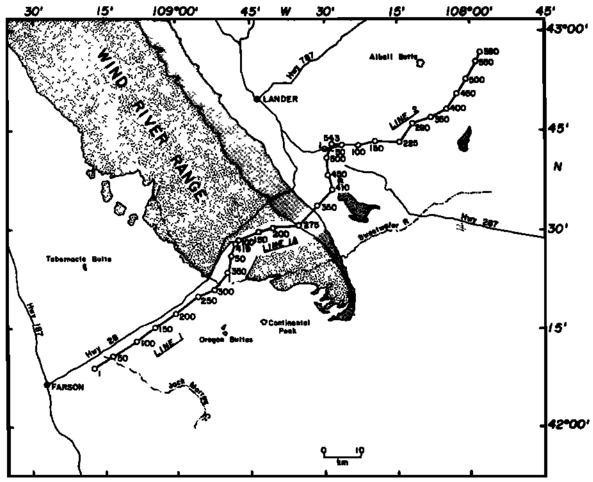

Fig. 1. Line location map of 3 continuous COCORP seismic profiles recorded across the south-east end of the Wind River Mountains, Wyoming. Coarse stipple pattern indicates Precambrian rock, fine stipple pattern indicates Paleozoic rock.

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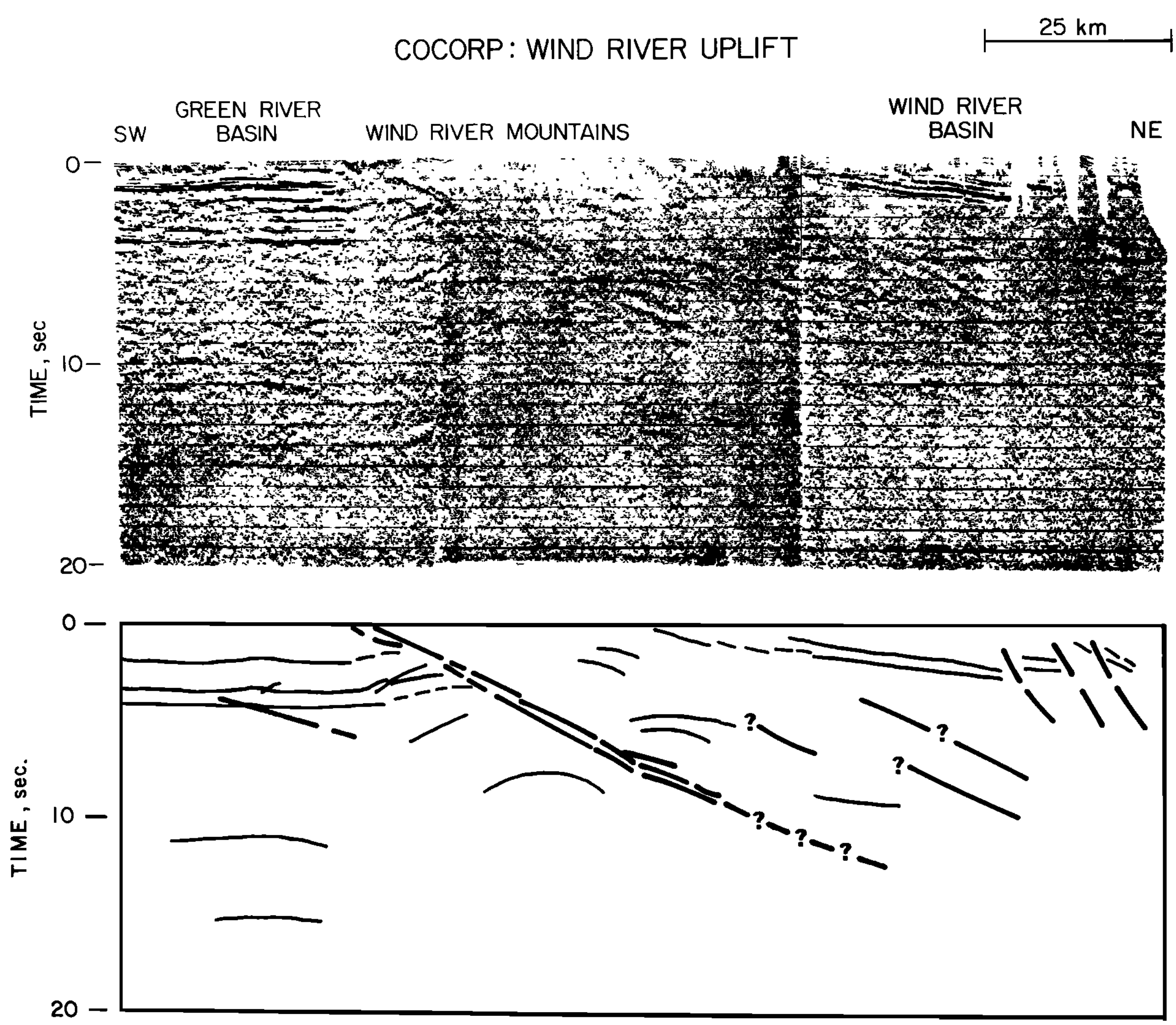

Fig. 2. COCORP seismic profiles recorded in the Wind River Mountains [top] and interpretation of some of the main features of the profiles [bottom]. Interpreted faults are indicated by thickened lines. Vertical scale on this figure is travel time of the seismic waves in seconds, and the relative positions of the events have not been corrected for velocity variations or geometry. To approximately convert travel time of seismic waves in crystal line basement to depth in kilometers, multi ply the travel time [in seconds] by 3. The Wind River thrust can be traced dipping to the north-east in the centre of the figure. Using changes in profile direction, the true dip of this thrust fault is 30° - 45°.

for a thrust fault is predicated by the Anderson theory of faulting [Anderson, 1951].

We consider a two-dimensional fault inclined to the vertical by the angle β, as shown in Figure 3. For two-dimensional faulting, it is appropriate to assume plane strain, so that $\varepsilon_{zz} = 0$. We further assume that σ_{xx} and σ_{yy} are principal stresses. The stress acting normal to the fault σ_n and the shear stress acting along the fault τ are given by [Jaeger and Cook, 1969].

$$\sigma_n = 1/2\ (\sigma_{xx} + \sigma_{yy}) + 1/2\ (\sigma_{xx} - \sigma_{yy})\ \cos 2\beta \quad [1]$$

$$\tau = -\ 1/2\ (\sigma_{xx} - \sigma_{yy})\ \sin 2\beta \quad [2]$$

The vertical stress σ_{yy} is assumed to be lithostatic and the horizontal stress σ_{xx} lithostatic plus a depth dependent compressive tectonic stress $\sigma_o(y)$,

$$\sigma_{yy} = \rho g y,\ \sigma_{xx} = \rho g y + \sigma_o(y) \quad [3]$$

In order to relate the normal and shear stress on the fault we assume that the Coulomb frictional law is applicable [Jaeger and Cook, 1969] with the result

$$|\tau| = S_o + \mu\ (\sigma_n - P_c) \quad [4]$$

where S_o is the inherent shear strength, μ the coefficient of friction and P_c the pore pressure. We assume pore pressure on the fault to be a fraction f of the hydrostatic pressure, so that

$$P_c = f \rho_w g y \quad [5]$$

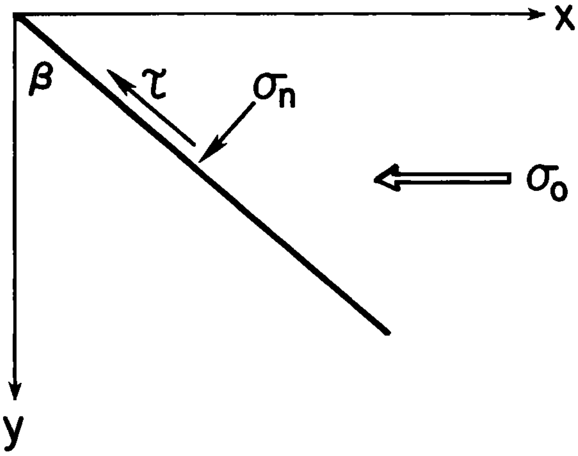

Fig. 3. Orientation of stress system during formation of the Wind River thrust. The tectonic stress σ_o is assumed horizontal.

where ρ_w is the density of water. If the fault is dry, then f = 0, and if the fault is sufficiently permeable to allow interconnected permeability to the surface, then f = 1. [If the fault were wet and there was no interconnected permeability to the surface, then f might be greater than 1, resulting in lower estimates of tectonic stress and shear stress than those given below.] Combining [1] to [5] gives:

$$\sigma_o = \frac{2\ [S_o + \mu g(\rho - f\rho_w)y]}{\sin 2\beta - \mu(1 + \cos 2\beta)} \qquad [6]$$

It is hypothesized that faulting occurs at the angle β_o for which σ_o is a minimum

$$\tan 2\beta_o = -\frac{1}{\mu} \qquad [7]$$

Substitution of this result into [6] gives

$$\sigma_o = \frac{2(1 + \mu^2)^{1/2}\ [S_o + \mu(\rho - f\rho_w)yg]}{1 - \mu\ [(1 + \mu^2)^{1/2} - \mu]} \qquad [8]$$

For the Wind River thrust fault we take the average angle of dip in the crust to be 35° or β_o = 55° and from [7] we find that μ = 0.36. In order to obtain σ_o it is necessary to specify S_o and f as well as the depth. At a depth of 10 km with S_o = 0 we find that σ_o = 2.9 kb for f = 0 [no pore pressure] and σ_o = 1.8 kb for f = 1 [hydrostatic pore pressure]. The corresponding values of the shear stress on the fault are τ = 1.3 kb and τ = 0.9 kb respectively.

Discussion

An important question is why should the Anderson theory be applicable? This thrust fault developed in basement rock of Precambrian age. The rocks exposed in the Wind River range have a long and complex history [Bayley et al., 1973] and many pre-Laramide fault and joint systems certainly existed. Under Laramide compressional tectonic stress a number of these preexisting faults and joints may have been reactivated to form the Wind River thrust. Although originally developed for the fracture of homogeneous rock the Anderson theory of faulting will predict the angle of dip of the activated fractures in a rock mass pervaded by fractures in random directions. For a specified coefficient of friction the theory predicts which fractures will be activated. The bifurcations and complexities of the fault zone seen on the COCORP profiles [Figure 2] might be explained by the reactivation of preexisting faults and joints. Surface geological studies of the Precambrian exposed in other Laramide basement uplifts suggest that some Laramide trends might be influenced by Precambrian structures [Hoppin and Palmquist, 1965; Tweto, 1975].

The dip of the Wind River thrust indicates that a coefficient of friction, μ = 0.36, was operative during the movement along it. Byerlee [1978] obtained an average value of the coefficient of friction of 0.6 - 0.8 for laboratory experiments under a wide range of experimental conditions. The lower value obtained in our calculations may be due to the different scales involved or may reflect the presence of phyllosilicate gouge minerals, enhancing the ease of movements [Byerlee, 1978].

Brittle behavior is implied if the Anderson theory and the concept of a coefficient of friction are applicable. On the San Andreas fault, earthquakes occur frequently to depths of 12 km, indicating brittle behavior. On thrust faults temperatures are likely to be lower than on strike-slip faults because total displacements and the resulting frictional heating are in general less; therefore, on the Wind River thrust fault brittle behavior could be expected to a depth of about 20 km.

Weathers et al., [1979] have determined stress levels on the Moine Thrust zone during active thrusting. Deviatoric stress levels determined from dislocation densities range from 1 - 2 kb. The deformation on the relatively thin [∿ 1m] fault zone was plastic and probably occurred at a depth of about 5-10 km. Although these values are in reasonably good agreement with ours the comparison raises several questions. To what depth does brittle behavior extend? Can the concept of a coefficient of friction be applied to the plastic behavior of a fault in much the same way that Anderson applied it to the failure of homogeneous rock? Birch [1964] has suggested that friction on faults separating upper crustal blocks, rather than plasticity within the blocks, may be an important factor in the deformation of the crust.

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