Seismic anisotropy due to preferred mineral orientation observed in shallow crustal rocks in southern Alaska

Thomas M. Brocher
U.S. Geological Survey, M.S. 977, 345 Middlefield Road, Menlo Park, California 94025
Nikolas I. Christensen
Department of Earth & Atmospheric Sciences, Purdue University, West Lafayette, Indiana 47907

ABSTRACT

Laboratory velocity measurements and structural field relations explain the observation of a significant seismic anisotropy within highly foliated rocks in southern Alaska. The orientation of the principal compressive stress indicates that this anisotropy is not related to extensive dilatancy, but can be satisfactorily explained by the foliation of the metasedimentary rocks. Laboratory measurements indicate a significant anisotropy within these rocks even at pressures well above those thought to close microcracks. These observations document that anisotropy related to preferred mineral orientation may be widespread in continental rocks. Thus, pervasive foliation can play a more important role in causing anisotropy than dilatancy, and inferences of principal stress orientations solely from anisotropy may be erroneous.

INTRODUCTION

Surface exposures of metamorphic terranes show planar structures such as slaty cleavage, schistosity, and foliation, which have developed in response to penetrative flow, that are often pervasive for tens to hundreds of kilometres. In such rock, preferred orientation of minerals is widely prevalent and the crust is highly anisotropic to seismic waves.

Seismic anisotropy studies can complement conventional refraction profiling by providing additional information on rock type and fabric. Seismic anisotropy thus is of considerable importance for geological studies and constitutes an important tool in the characterization of the subsurface. In this paper we present the results of an investigation of the seismic anisotropy within accreted rocks in southern Alaska using seismic refraction, laboratory measurements of the elastic properties of hand samples, field structural relations, and estimates of principal stress directions.

The study was conducted within the Valdez Group of the Chugach terrane in southern Alaska (Fig. 1A). The Chugach terrane consists of accreted deep-sea sedimentary and oceanic crustal rocks that form a continuous belt approximately 2000 km long and 60–100 km wide, extending from central British Columbia to the Aleutian arc (Plafker et al., 1977). The Upper Cretaceous Valdez Group consists primarily of pelitic schist, metagraywacke, and metabasalt that have been metamorphosed in the study area to lower greenschist facies (Winkler and Plafker, 1981; Winkler et al., 1981; Plafker et al., 1989a). In the northern and northeastern parts of the study area (Fig. 1B), Jurassic and older rocks are thrust southward over the Valdez Group along the Border Ranges fault system.

In the study area, the Valdez Group (Fig. 1B) consists of multiply deformed, interbedded metagraywacke and fine-grained schistose to mylonitic pelitic phyllites (Plafker et al., 1989a; Nokleberg et al., 1989). Structural cross section A–A′ in Nokleberg et al. (1989) shows broad open folds to the north that progressively decrease in wavelength toward the south. These second- and third-generation folds are defined by the northern and southern dips of the first-generation schistosity (Fig. 1B). The average strike of first-generation schistosity and axial planes of sparse parallel isoclinal folds in the northern part of the southern Valdez Group is 78°; the dip is 58°N (Nokleberg et al., 1989). These structures, as shown in Figure 1B, are rotated to south dips in the center of the study region. Major and minor second-generation fold planes in the southern Valdez Group have an average strike of east-west (Nokleberg et al., 1989), although Figure 1B shows that the predominant dip direction is to the south in the center of the study region. Major and minor second-generation fold planes in the southern Valdez Group have an average strike of east-west and a steep dip, whereas major third-generation structures consist of a few large antiforms and synforms trending east-west (Nokleberg et al. 1989). Fourth-generation structures consist of well-developed cleavage striking on average 008° and dipping 85° to the east (Nokleberg et al., 1989). The 1.5 km of structural relief exposed within the study area suggests that the steep foliation dips observed in outcrop can be reasonably extrapolated to subsurface depths of 1 to 2 km.

In February 1986, the U.S. Geological Survey acquired 107 km of multichannel seismic-reflection data along the north-south-trending Richardson Highway in southern Alaska (Fisher et al., 1989). These data were acquired in support of the Trans-Alaska Crustal Transect (TACT), a comprehensive geological and geophysical study of the crust within a corridor across Alaska (Page et al., 1986). Parameters used to acquire this seismic-reflection line have been summarized by Fisher et al. (1989). Nominal source-to-receiver offsets exceed 15 km, and because of the long offsets, these data have been used for a high-resolution refraction study of the crust along the reflection profile (Brocher et al., 1989).

RESULTS

Interpretations of seismic-reflection profiles and the refraction data (Fisher et al., 1989; Plafker et al., 1989a) suggest that the Valdez Group flysch rocks extend to subsurface depths of at least 10 km in the study area. Laboratory measurements of phyllitic rocks demonstrate that significant velocity anisotropy is present within the Valdez Group. Compressional wave velocities are shown as a function of pressure in Figure 2 for three mutually perpendicular propagation directions in a sample of phyllite. The lower velocities were measured normal to foliation (i.e., for propagation approximately north-south in the study area), whereas the two higher velocity curves are velocities measured within the foliation plane. The high anisotropies observed at elevated confining pressures are consistent with earlier findings that compressional wave seismic anisotropies in metamorphic rocks originate primarily from preferred mineral orientation (Christensen, 1965, 1966).

Average velocities at 50 MPa measured for seven field-oriented phyllite samples (Fig. 1A) of the Chugach terrane normal to the foliation

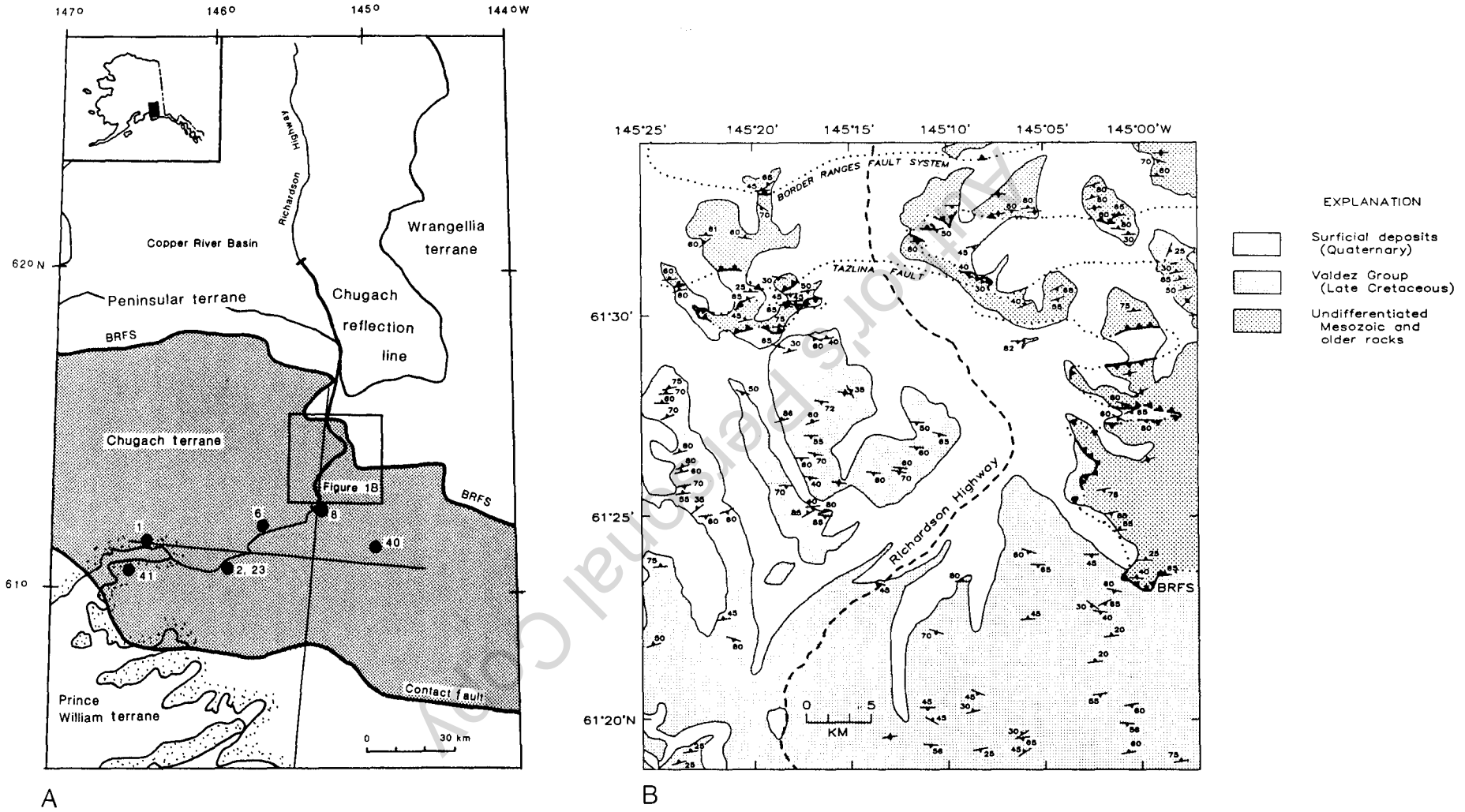

Figure 1. A: Map of study area showing location of Chugach seismic-reflection line along Richardson Highway, reconnaissance refraction lines (thin solid lines), and seven hand-sample localities (numbered solid circles). Chugach terrane is bounded to north by Border Ranges fault system (BRFS) and to south by Contact fault system. This map is simplified from Figure 2 of Plafker et al. (1989a). Inset shows location of study area. B: Detailed map of study area showing strike and dip of foliations within phyllites of Valdez Group, as well as location of thrusts associated with Border Ranges fault system. Simplified from Plafker et al. (1989b).

and within the foliation parallel to strike were fit to the 2 θ terms of the Backus equation (Backus, 1965), relating velocity to azimuth. This anisotropy, predicted from the laboratory measurements, is shown in Figure 3 for foliation dips of 45°, 60°, 75°, and 90°. In order to generate this figure, we assumed that the phyllites strike east-west. Inasmuch as the fastest direction in the laboratory measurements is parallel to the foliation, Figure 3 suggests that the fastest directions measured in the field should be oriented approximately east-west.

Brocher et al. (1989) noted that the bend in the seismic-reflection line in the study area (Fig. 1B) allowed the determination of compressional-wave velocity within the Valdez Group at two distinct azimuths. Observed first-arrival times shown in their Figure 13 were used to determine the measured field velocities plotted in Figure 3 for orientations of 0° and 50° from north. In agreement with the predicted field velocities shown in Figure 3, measured field velocities at 50° from north are about 9% faster than those whose orientation is due north-south. The uncertainties in the measured field velocities are about 0.1 km/s, much lower than the 0.5 km/s difference between the measured velocities for the two different azimuths. Forward modeling of the observed field traveltimes indicates that this anisotropy begins at a depth of 1 km beneath the surface; Brocher et al. (1989) indicated that the anisotropy persists to a depth of at least 1.5 km. The raypaths used for the study are located either under or to the west of the Richardson Highway near the center of the area shown in Figure 1B and thus do not sample the more complex structure to the north and east of the Border Ranges fault system.

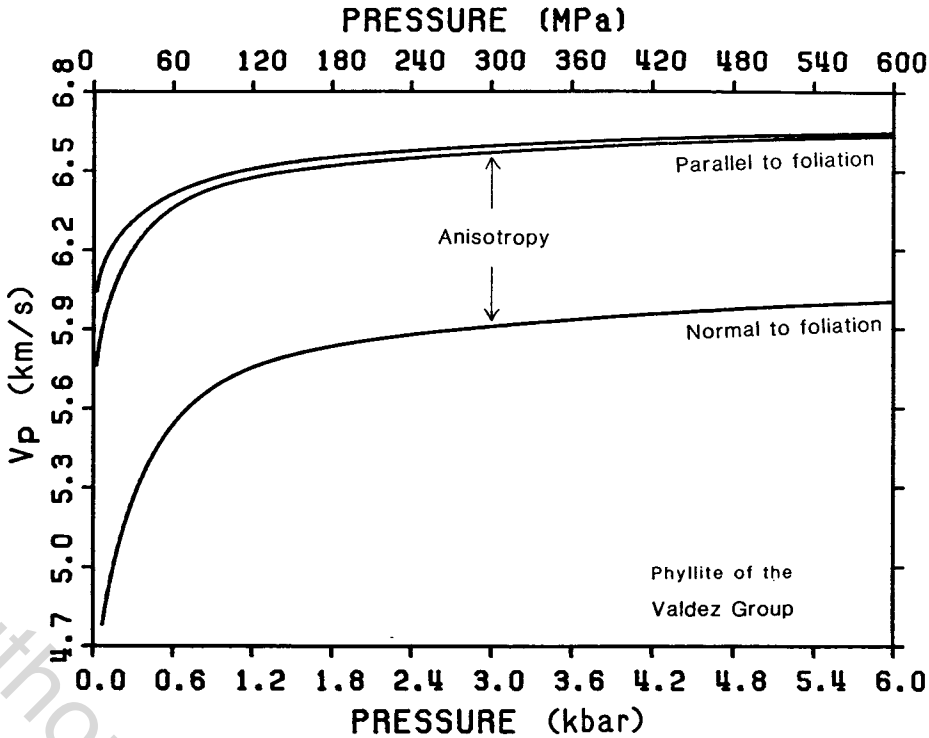

Figure 2. Compressional wave velocities as function of hydrostatic pressure in sample of phyllite from Valdez Group for three perpendicular propagation directions. Low velocities are for propagation normal to foliation.

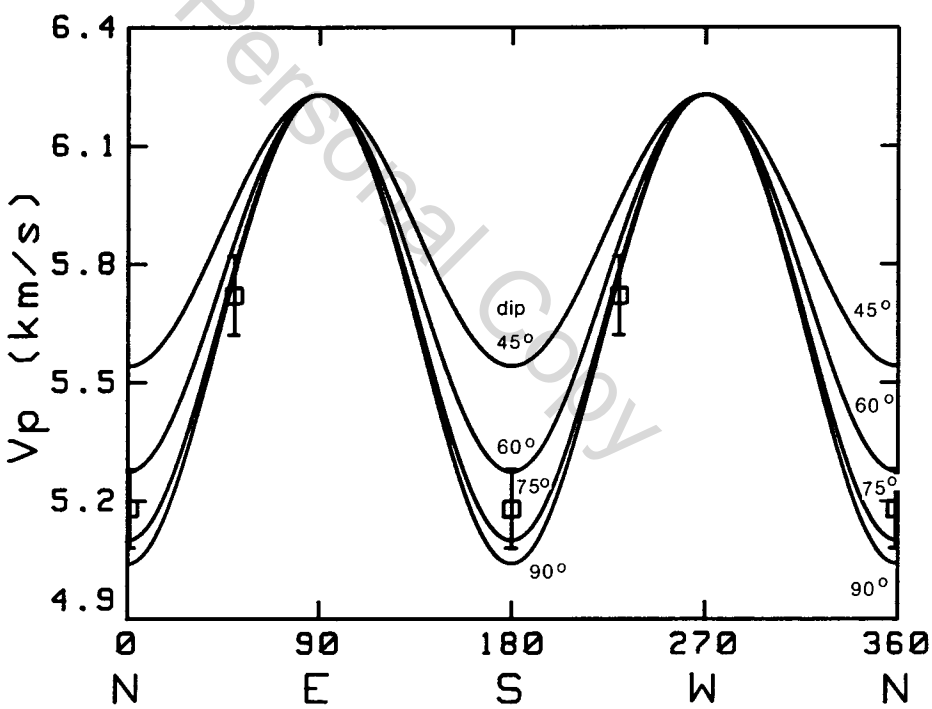

Figure 3. Predicted velocities for phyllite from Valdez Group as function of azimuth, assuming east-west strike for dips of 90°, 75°, 60°, and 45°. Squares with error bars show measured field velocities obtained from observed first-arrival traveltimes shown in Figure 13 of Brocher et al. (1989).

DISCUSSION

Recently proposed models for seismic anisotropy based on vertical cracks oriented by the ambient stress field predict that the fastest direction of seismic-wave propagation should be parallel to the direction of maximum compressive stress (Crampin, 1987). This proposed stress-induced anisotropy has been called the extensive-dilatancy model. Estimates of the orientation of the maximum compressive stress in southern Alaska based on focal mechanisms and trilateration studies (Biswas et al., 1986; Savage and Lisowski, 1988; Page et al., 1989) range from approximately due north-south to N32°W. Thus, if these lithospheric-scale stress indicators can be extrapolated to the smaller scale study region, the extensive-dilatancy model for anisotropy would predict the fast direction of propagation to be in the north-south to N32°W direction, which is incompatible with our observations (Fig. 4). The pervasive-foliation model is consistent with the observations.

The results reported here are significant for several reasons. The growth of continents through the tectonic accretion of sediments, as in Alaska, is now recognized to be an important process for much of the geologic history of the Earth. Thus, we expect that seismic anisotropy related to preferred orientation of highly foliated rocks is widespread throughout the continents. This suggestion receives support from the observation of seismic anisotropy within highly schistose rocks in the Leech River Complex of Fairchild and Cowan (1982) on Vancouver Is-

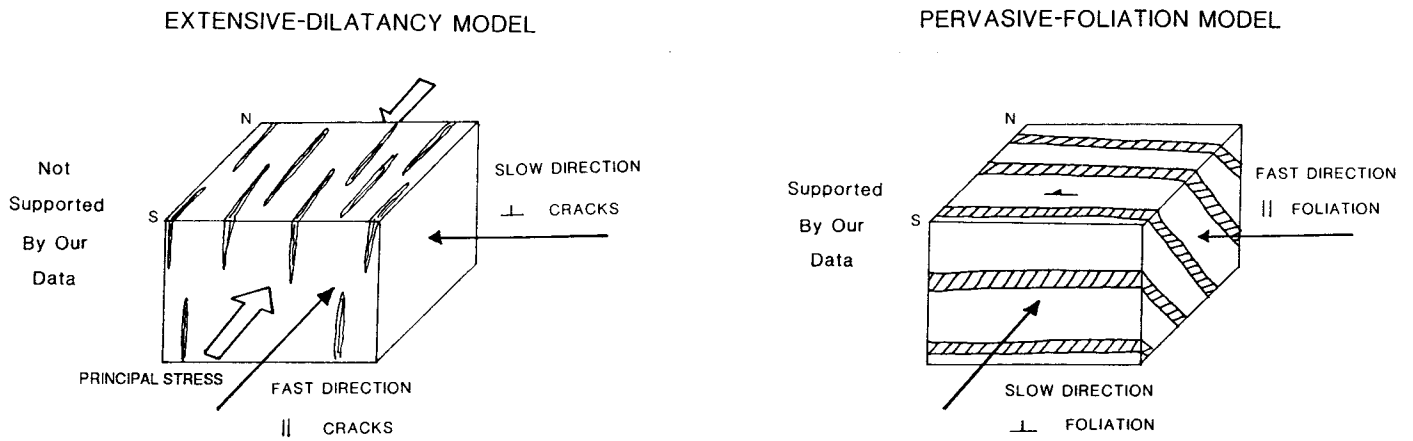

Figure 4. Schematic comparison of models for seismic anisotropy within Valdez Group. Extensive-dilatancy model predicts velocity and anisotropy that are not consistent with our observations, whereas anisotropy predicted by pervasive foliation of metasedimentary units is.

land (Mayrand et al., 1987). This conclusion, in turn, suggests that caution in interpreting crustal composition from reconnaissance refraction–wide-angle-reflection profiling along one azimuth should be exercised.

Equally important is the need to recognize that preferred mineral orientation due to foliation of metamorphic rocks is a pervasive and important mechanism for the generation of seismic anisotropy within the continental crust, even at shallow depths. Although oriented cracks are an important source of seismic anisotropy, particularly within the upper part of the igneous oceanic crust (Stephen, 1981), our results reemphasize the need to recognize other important sources of anisotropy, especially within continental metamorphic terranes. Our results also indicate that the inference of principal stress directions from measurements of seismic anisotropy may lead to erroneous determinations of these stress directions. We conclude that seismic anisotropy within many regions of the upper continental crust "isn't all that it's cracked up to be."

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