GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 10, PAGES 2129-2132, MAY 15, 2001

Nanga Parbat crustal anisotropy: Implications for interpretation of crustal velocity structure and shear-wave splitting

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Abstract. The Nanga Parbat - Haramosh massif represents a unique exposure of mid-lower continental crust from beneath the Himalayan orogen. Seismic velocity measurements on a suite of quartzofeldspathic gneisses show up to 12.5% velocity anisotropy for compressional waves and up to 21% for shear waves. The degree of anisotropy is a function of mica content and rock fabric strength. Over 30% of the samples have maximum compressional wave velocities of 6.4-6.5 km/s; velocities typically associated with more mafic lithologies. These results have implications for the interpretation of crustal velocity structure obtained from wide-angle seismic surveys where in situ velocity measurements are made from refracted or turning rays that potentially spend a substantial portion of their travel path propagating in the foliation plane. Velocities determined from these surveys may overestimate mean velocities of crustal rocks with well-developed horizontal fabric. In addition, crustal anisotropy due to the development of pervasive rock fabric has the potential to be a significant contributing factor to shear-wave splitting observations.

1. Introduction

Sitting at the intersection of the Karakorum, Himalaya, and Hindu Kush mountain ranges, the Nanga Parbat - Haramosh massif, on the northernmost edge of the western Himalayan syntaxis, represents an unusual north-south extension of Indian crust into the Karakorum of Asia (Figure 1). The rocks of the massif are Pre-Cambrian (1.8Ga), Indian basement gneisses, continental crust exhumed from beneath the overlying plate [*Butler and Prior*, 1988; *Treloar, et al.*, 2000; *Zeitler et al.*, 1989]. The massif has an areal extent of over 5000 km^2. To the west and east lie mafic rocks of the Late Cretaceous and Eocence Kohistan-Ladak Island arc captured during the collision of India and Asia. The contact between the island arc and Indian plate rocks is the Main Mantle thrust, equivalent to the Indus suture in the central and eastern Himalaya. The Precambrian Indian crust making up Nanga Parbat exhibits a polymetamorphic history including an early Pre-Himalayan high-grade metamorphic event overprinted by metamorphism acquired in the Tertiary as Indian lithosphere subducted beneath Asia [*Poage et al.*, 2000; *Treloar, et al.*, 2000; *Zeitler et al.*, 1989]. Rapid uplift and denudation in the last 10Ma has exposed a mid-lower crustal section from beneath the overlying upper plate [*Zeitler et al.*, 1993].

Nanga Parbat is mapped as a crustal pop-up structure with uplift of the massif accommodated along high-angle faults and shear zones within the interior of the massif [*Edwards, et al.*, 2000; *Schneider et al.*, 1999]. The massif consists of granitic and metasedimentary gneisses, and granitic orthogneisses that make up a basement complex. A cover sequence of calc-silicates and marble, sedimentary sequences on top of basement, was subducted along with the basement during collision and metamorphosed.

The bulk of the massif is composed of amphibolite grade pelitic rocks. The primary metamorphic assemblage is a muscovite - aluminosilicate bearing assemblage including quartz, muscovite, biotite, garnet, and plagioclase, ±kyanite, ±sillimanite [*Poage et al.*, 2000]. The core of the massif contains a granulite grade metamorphic mineral assemblage accompanied by anatectic cordierite bearing granitic veins indicating metamorphic conditions at or near the granite solidus [*Poage et al.*, 2000; *Whittington et al.*, 1998]. Young migmatites exposed in the core of the massif were metamorphosed under low-pressure high-temperature conditions (~4-6 kbars, 600-700°C) 3 Ma ago and represent in-situ partial melting of host rocks [*Poage et al.*, 2000; *Whittington et al.*, 1998; *Zeitler et al.*, 1993] (Figure 1). Peak metamorphic conditions along the margins of the massif are more typical of temperature and pressure conditions found deeper in the crust (Figure 1). Thermobarometric estimates of final equilibration along the flanks is ~7-11 kbars (25-40 km depth), 550-700°C [*Poage et al.*, 2000]. Farther east deeper portions of the crust are exposed. Peak metamorphic conditions along the eastern margin are ~11-14 kbars (40-50 km depth), 675-800°C [*Poage et al.*, 2000].

As part of a multidisciplinary study investigating the active tectonic processes responsible for recent uplift and crustal reworking at Nanga Parbat we deployed a temporary seismic array to record local and regional earthquakes to determine crustal structure and fault kinematics of the massif [*Meltzer et al.*, in press]. As part of the seismic study we collected a suite of bedrock samples from sites where we located our seismometers in order to make laboratory measurements of seismic velocities to help constrain tomographic models of velocity and attenuation from earthquake data. Samples were collected from the massif over an approximately 50 x 50 km area and over 4 km of vertical relief providing a rep-

Paper number 2000GL012262.
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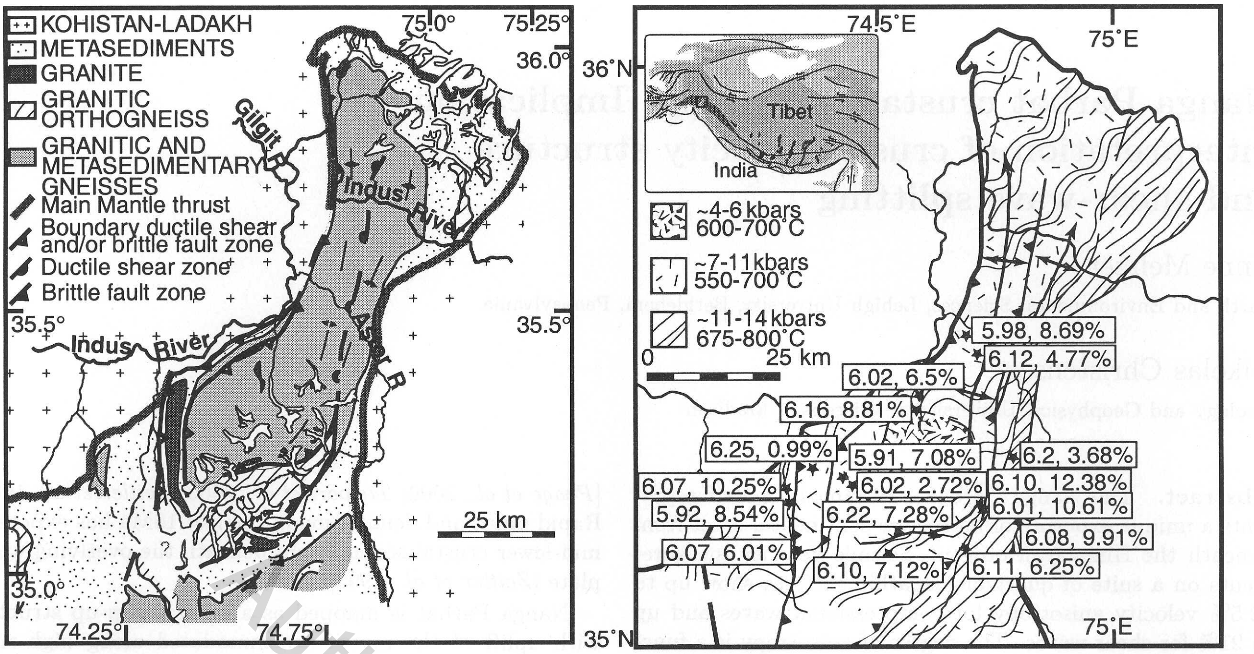

Figure 1. Left:Geologic map Nanga Parbat-Haramosh Massif (after Schneider et al. 1999). Right: Maximum pressure-temperature estimate of final equilibration (after Poage et al, 2000), sample locations (stars), and mean Vp in km/s and P-wave anisotropy of Nanga Parbat samples. Inset: location map with Nanga Parbat-Haramosh massif outlined by box.

resentative suite of samples for analysis (Figure 1). In this paper we report the laboratory measurements from the felsic gneisses and note their implications for interpretation of crustal velocity structure and shear-wave splitting results.

2. Laboratory Techniques

Three mutually perpendicular cores were removed from each of 19 samples (Figure 1). For banded and foliated rocks one core was taken normal to the planar structure, while the remaining two were oriented with their axes in the foliation plane (Figure 2). Of these two, one was oriented parallel to the lineation if present. Velocities in each core were measured at room temperature and hydrostatic pressures up to 1000 MPa (equivalent to ~35 km depth) using the pulse transmission technique [*Christensen*, 1985]. Readings were taken at 20, 40, 60, 80, 100, 200, 400, 600, 800 and 1000 MPa and repeated for downgoing pressures. For a subset of the 19 samples, five of the gneisses and 1 granite, two shear velocity-pressure runs were made for each core, giving a total of six shear velocity data sets per rock. For cores cut with their axes parallel to foliations the vibration directions of the shear waves were parallel and perpendicular to foliation which provides data on maximum shear wave splitting [*Christensen*, 1966]. Shear wave vibration directions for cores taken perpendicular to foliations were parallel to the axes of the cores cut in the foliations.

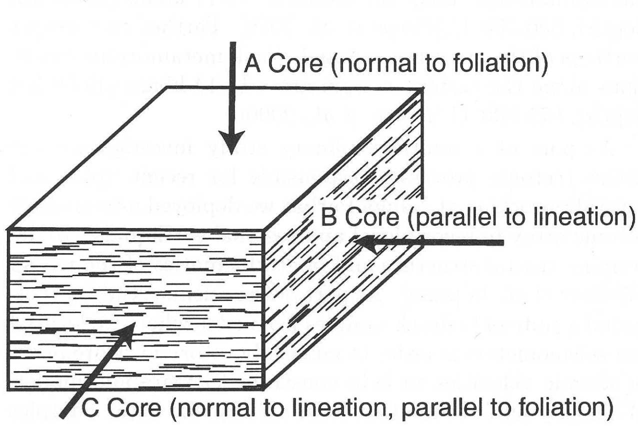

Figure 2. Core orientations with respect to foliation.

3. Results

Mean Vp (the average of the 3 cores from each sample) for the 19 samples varies from 5.91 to 6.25 km/s (Figure 1). All velocities are reported at pressures of 1000 MPa, approximately 35 km depth. At these pressures, all microcracks are presumed closed. Vp anisotropy for the gneisses varies from 2.7-12.5% and averages 7%. The degree of anisotropy directly correlates with the amount of mica present in the rock and rock fabric strength. Rocks with equal amounts of mica exhibit a range of anisotropy depending on the orientation and alignment of the mica in the sample (Figure 3). Gneisses with average to high anisotropy ($\geq$6%) have well developed rock fabric, the mica is segregated into distinct bands and individual grains are elongated with their long axes oriented parallel to one another. Gneisses that exhibit low anisotropy lack well developed fabric; the mica is relatively disseminated in the sample, individual grains tend to be relatively equidimensional in cross section, and cleavages are aligned at oblique angles to one another. Even though mica constitutes approximately 18 to 35% by volume of the gneisses it is clearly the main cause of the observed anisotropy. Single crystal velocity measurements of muscovite and biotite show that propagation velocities measured parallel to the tetrahedral sheets are as high as 8 km/s, while velocities measured perpendicular to the sheets are only 4-5 km/s [*Alexandrov and Rhyzhova*, 1961; *Vaughan et al.*, 1986].

Samples with a well developed rock fabric but lacking mica or containing only a small percentage of mica exhibit a

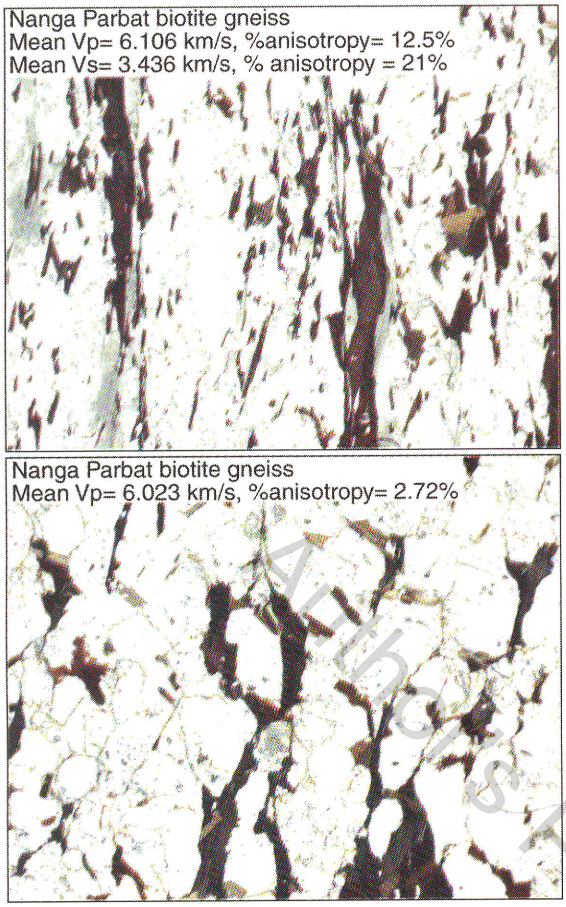

Figure 3. Thin sections from two samples of Nanga Parbat gneiss. Top: biotite grains are segregated, elongated, and aligned parallel to one another resulting in significant velocity anisotropy. Bottom: biotite grains are more disseminated, equidimensional, and oriented at oblique angles resulting in low velocity anisotropy.

much smaller degree of anisotropy these include a mylonite (3.7% anisotropy, ~7% mica), a marble (4.3% anisotropy, 0% mica), and a pyroxene granulite (2.2% anisotropy, 0% mica). As expected, rocks without fabric, such as the young undeformed granitic pluton, are virtually isotropic (1% anisotropy).

While the mean compressional velocities from all three cores from each sample fall within the norm for rocks of felsic composition, 5.91-6.25 km/s [*Christensen and Mooney*, 1995], velocities measured perpendicular and parallel to foliation show a much wider range and degree of separation, in fact not overlapping at all (Figure 4). Velocities measured perpendicular to foliation (slow) range from 5.6 to 6.0 km/s and average 5.8 km/s. Velocities measured in the foliation plane (fast) range from 6.1-6.5 km/s with over a third of the samples having maximum compressional wave velocities of 6.4-6.5 km/s, velocities typically associated with rocks of more mafic composition such as diorites.

Shear wave velocities were measured on a subset of the 19 samples, five gneisses and one granite. Mean Vs for each sample varies from 3.4-3.55 km/s. Velocity anisotropy for shear waves is larger than that observed for compressional waves ranging from 8.5-21% and averages 12.9%. The minimum and maximum shear wave velocities show an even greater degree of separation than that found for compressional velocity. Minimum Vs for the 5 samples measured ranges from 3.13-3.42 km/s while the maximum ranges from 3.65-3.86 km/s (Figure 4).

4. Implications for Seismic Field Studies

The observed velocity heterogeneity and anisotropy in rocks that would normally be considered monotonously homogeneous from a seismological perspective have several implications for the interpretation of velocity structure from crustal scale seismic surveys and the use of shear waves to help unravel crustal structure and constrain composition.

The Nanga Parbat gneisses, which are typical of paragneisses found in many orogens, are compositionally very similar to one another averaging 17% quartz, 54% plagioclase, and 24% mica. The range of mean velocities of individual samples, 5.91-6.25 km/s, reflects minor variations in the bulk mineralogy of the samples and the overall heterogenity of these relatively homogeneous felsic crustal rocks. While the mean velocity of all the samples measured is 6.1 km/s the true mean velocity variation has a range of 0.34 km/s and is scale independent. This velocity heterogeneity provides a partial explanation for the spectral characteristics of the wavefield recorded in crustal scale seismic surveys [*Holliger*,, 1997; *Levander et al.*, 1994].

Both outcrop exposures and crustal seismic surveys suggest that the mid-lower crust is generally layered at multiple scales. If the mid to lower crust has a well developed fabric, then in situ velocity measurements made from refracted or turning rays that spend a substantial portion of their travel path propagating in the foliation plane may systematically overestimate the average velocity of these rocks. In the ab-

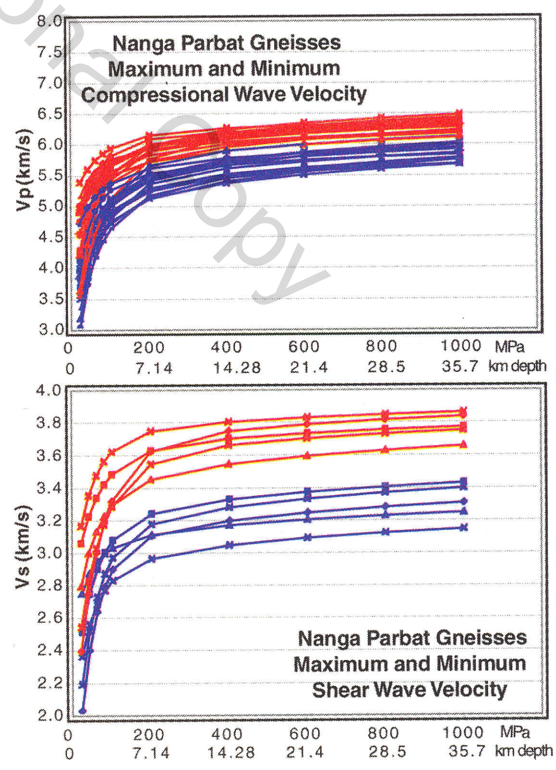

Figure 4. Minimum (blue) and maximum (red) compressional (top) and shear (bottom) wave velocity versus pressure for Nanga Parbat gneisses (see text for discussion).

sence of any other constraints, compressional wave velocities of 6.4-6.5 km/s would generally be interpreted as representing rocks of intermediate composition where in fact they could be explained by felsic gneisses with well developed, pervasive, coherent, horizontal foliation. Likewise seismic velocities measured for propagations at high angle to foliations would range from 5.6 to 6.0 km/s. At pressures corresponding to midcrustal depths velocities in this range are significantly lower than mean velocities of common plutonic and metamorphic rocks (e.g. Christensen 1995) and would likely be interpreted to result from high geothermal gradients or possibly high pore pressures. An additional implication of the observed velocity variation and anisotropy is that changes in observed crustal velocity profiles with depth do not necessarily imply or require a change in composition with depth. The envelop of velocities plotted in Figure 4 show that a change in P-wave velocity from 5.0-5.5 km/s in the shallow crust to 6.0-6.5 km/s in the mid to lower crust can be accounted for within a rock of uniform composition.

Measured shear wave velocity anisotropy varies from 7-21% and averages 12.4%. If the rock fabric is coherent over relatively large distances, then crustal anisotropy can be an important contribution to shear wave splitting observations. For shear-wave splitting observations made using teleseismic arrivals, this would require that the rock fabric be aligned in a relatively vertical orientation such as might be expected in a deformed orogen. The average anisotropy observed in the Nanga Parbat gneisses will contribute up to 0.2 s ∂t_s over a propagation distance of 5 km, up to 0.4 s ∂t_s over a propagation distance of 10 km, and over 1.5 s ∂t_s over a propagation distance of 40 km (an average crustal column turned on end)[*Percival and Card*, 1983]. At Nanga Parbat shear wave splitting is observed in the local events and provides a mechanism to map crustal deformation at depth. Observations of shear-wave splitting in wide-angle active source experiments to date are rare [*Clement et al.*, 1994], partly because of a tendency to record single channel vertical component data in active source experiments, partly because of the difficulty in generating and recording good shear waves, and partly because establishing an appropriate field geometry is difficult. However, with careful experimental design, observations of shear wave splitting can be used to determine if pervasive rock fabric has biased interpretation of crustal velocity structure in places.

Systematic recording of high-quality 3 component data and observations of crustal anisotropy in future seismic field investigations using regional or local earthquakes or active source techniques will be a powerful tool to provide better constraints on composition and to map rock fabric and deformation in the crust. This, in turn, will provide us with a greater understanding of the geologic processes that have formed continental crust. Metamorphic massifs consisting of lithologies similar to those of Nanga Parbat are ideal for such investigations.

Acknowledgments. This research is supported by the Continental Dynamics Program, Earth Sciences Division, National Science Foundation (EAR-9418849) We thank Changxing Long for laboratory measurements.

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(Received August 25, 2000; revised January 22, 2001; accepted February 7, 2001.)