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Crustal Structure of Yunnan Province, People's Republic of China, from Seismic Refraction Profiles

Rong-Ju Kan, Hong-Xiang Hu, Rong-Sheng Zeng,
Walter D. Mooney, Thomas V. McEvilly*

Seismic refraction profiles in Yunnan Province, southwestern China, define the crustal structure in an area of active tectonics on the southern end of the Himalaya-Burma arc. The crustal thickness ranges from 38 to 46 kilometers, and the relatively low mean crustal velocity indicates a crustal composition compatible with normal continental crust and consisting mainly of meta-sedimentary and silicic intrusive rocks, with little mafic or ultramafic component. This composition suggests a crustal evolution involving sedimentary processes on the flank of the Yangtze platform rather than the accretion of oceanic island arcs, as has been proposed. An anomalously low upper-mantle velocity observed on one profile but not on another at right angles to it may indicate active tectonic processes in the mantle or seismic anisotropy.

We report results of a cooperative Sino-American geophysical investigation of crustal structure and tectonics in southwestern China. Yunnan Province, the area of study, is located at the eastern end of the Himalaya-Burma arc, just southeast of the Tibetan plateau (Fig. 1). Tectonically active, with major throughgoing faults, the region is highly seismic. The prominent Red River fault, for example, shows substantial recent movement (*1*) and is considered a boundary between major crustal blocks (*2*). Historical records yield evidence for some 40 major earthquakes (probably of magnitude 6 or greater) in the last 400 years (*3*). In this century such earthquakes have occurred at a rate of about three every 10 years. The largest recent shock in western Yunnan, of magnitude 7, severely damaged the old town of Dali in 1925. Chinese scientists have estimated a 120-year recurrence interval for the 1925-type earthquake.

Modern research on earthquakes in Yunnan began in 1965 when the Institute of Geophysics of the Academy of Science established a network of 12 seismographic stations in the province, complementing the Kunming station, which had been installed in 1956. The network has operated without interruption since then, growing to some 25 stations today, all of which are linked by continuous telephone or radio telemetry to the central recording and processing facility at the provincial Yunnan Seismological Bureau (YSB) in Kunming. YSB was established in 1975 to facilitate joint studies on earthquake prediction with the State Seismological Bureau (SSB) in Beijing. YSB has continued to upgrade its capabilities to bring them up to modern standards for seismological research. Twelve of the YSB stations are monitored by computer, with automated detection, digital recording, and real-time processing of the incoming signals.

The Xiaguan Experimental Site (XES), centered on Dali in western Yunnan Province, is one of two special study areas established in 1980 by SSB for especially concentrated and comprehensive research on earthquake prediction methods. Cooperative research projects, under the China–United States protocol on earthquake studies signed in 1980 (*4, 5*), are part of the planned scientific effort at XES. Included are studies of seismicity, Quaternary geology and faulting, crustal deformation, various premonitory earthquake phenomena, and deep crustal structure.

The cooperative project in deep crustal structure involves seismic refraction profiling conducted jointly by the Institute of Geophysics, SSB, and YSB, with United States participation supported by the U.S. Geological Survey and the National Science Foundation. We now present results from long refraction profiles carried out in Yunnan in 1982 for the purpose of relating crustal structure to seismotectonic processes.

Yunnan Province of southwestern China is an area of intraplate tectonics adjacent to an active collision boundary (Fig. 1) lying to the west of the stable Yangtze platform. The regional geology consists of early Paleozoic through late Mesozoic marine sedimentary rocks. It is locally intruded by granitic plutons, and, particularly in the western half of Yunnan, mafic and ultramafic rocks are exposed at high-angle faults. Some investigators have suggested that southwestern China evolved as a broad zone of accreted terrains (both continental and oceanic fragments) during the Phanerozoic eon (*2, 6, 7*). The current high rate of deformation of Yunnan is evident in the high level of historical and modern seismicity.

The faults of southwestern China occur with three different strike directions. Those of northwest strike extend from southern Yunnan to the Tibetan plateau, forming part of the Mediterranean-Himalayan tectonic belt. Faults of north-south strike occur to the east near 104°E longitude, at the transition from the tectonically active southwest to the eastern blocks of China. The throughgoing northwest-striking faults of western Yunnan are also intersected by some faults with northeast strike, but these are comparatively less active seismically.

Some Chinese investigators have characterized the active deformation in southwestern China in terms of a mosaic of crustal blocks, with deformation concentrated along the block boundaries (*6, 8*). An alternative model (*9*) describes the deformation in terms of the

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indentation of a plastic medium (Asian plate) by a rigid indentor (Indian plate). Others (*10, 11*) have emphasized the role of the reactivation of preexisting zones of weakness in contemporary seismicity and Quaternary faulting.

Three seismic refraction lines with combined length of 1070 km were recorded (Fig. 1). Because of the rugged terrain, the seismic lines were confined to the few existing roads. Lines 1 and 2, for example, used the Burma Road. Line 1 parallels the prevailing northwest-southeast trend of faulting in Yunnan, lying about 50 km northeast of the dominant Red River fault, and runs from the Kunming vicinity northwest into the XES. Lines 2 and 3 cross line 1 at its northern and southern ends, respectively, and are oriented nearly at right angles to the northwest-southeast fault trend.

The profiles were designed to investigate crustal structure over a broad region and to study the Red River fault system by crossing it both near Xiaguan, where earthquake activity is high, and south of Kunming, where the fault is currently aseismic. Several additional considerations governed the survey geometry. Reliable information about the crustal thickness and its variations was lacking for this region because no previous seismic refraction measurements had been made. Gravity data suggest a crustal thickness of some 50 km in central Yunnan, increasing northwesterly into Tibet (*12*). The 300- to 400-km line lengths with four shot points per line were designed to yield reliable determinations of crustal thickness from both wide-angle reflections and mantle refractions.

Within China some 250 standardized instruments for deep seismic sounding (DSS) are distributed among various national and provincial research groups that are part of the SSB. In the Yunnan study, the Institute of Geophysics and YSB joined forces with several other groups to deploy a total of 196 instruments at about 2-km spacing along each line. The instruments record on two-channel magnetic tape cassettes, one channel for timing control and the other for the seismometer signal; the latter is frequency modulation–multiplexed at two or three gain levels for wide dynamic range. The sensors are 2-Hz vertical-component seismometers. The record sections analyzed in this report were constructed in China from paper playouts of the individual seismograms. Two computers for digital playback and analysis were recently installed in Beijing and Yunnan by the American members of the cooperative program. Further analyses of these and future DSS data will be carried out according to digital data-processing techniques.

Four explosions of trinitrotoluene (1.5 to 3 metric tons) emplaced in 10 to 20 boreholes each 15 to 20 m deep, were shot on each line and yielded an average source spacing somewhat less than 100 km.

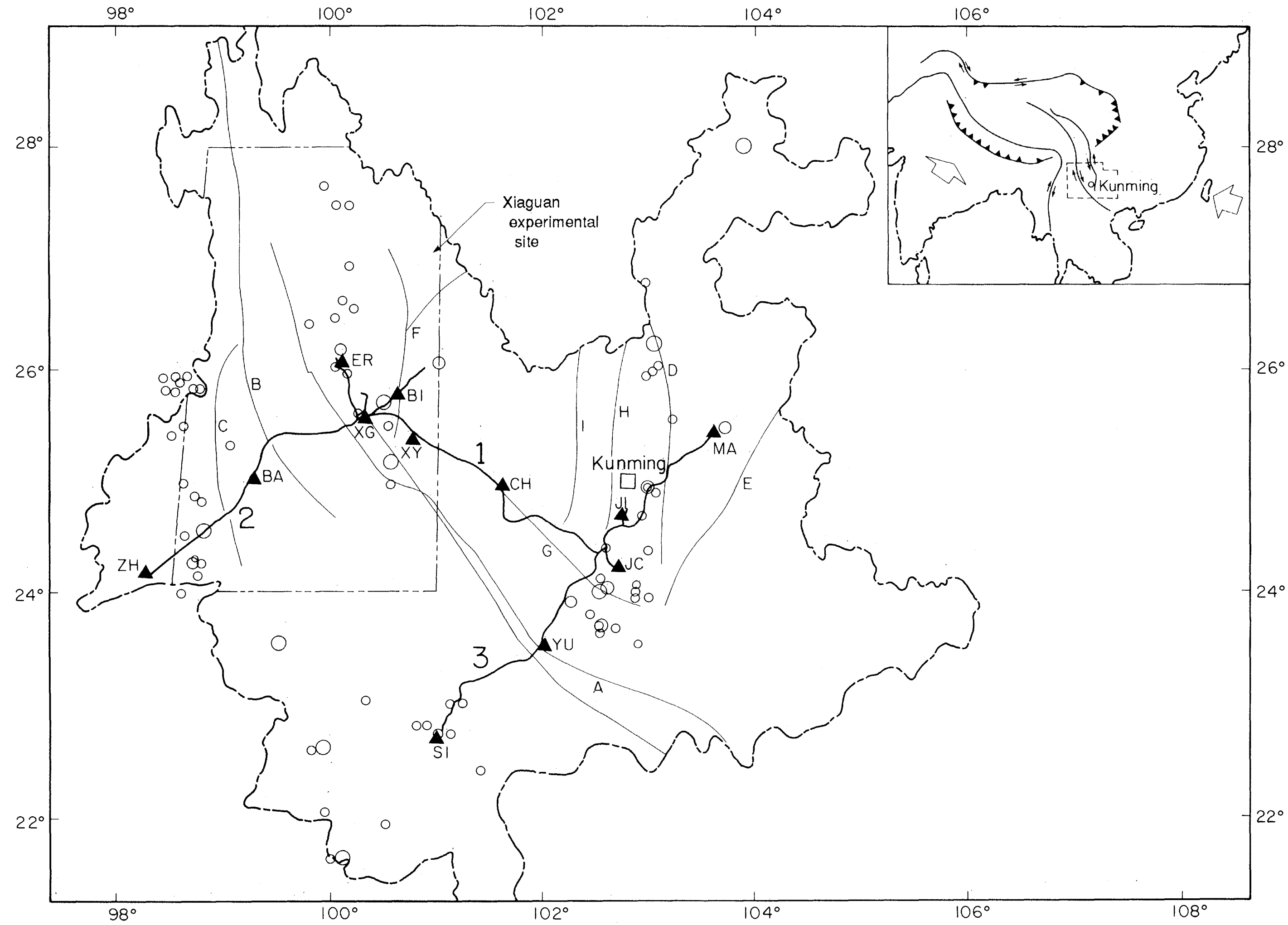

Fig. 1. Regional setting of Yunnan Province of southwestern China within the Himalaya-Burma arc (inset). Location map for seismic refraction lines 1, 2, and 3. Fault names are given by single-letter codes: A, Red River; B, Lancang; C, Nujiang; D, Xiaojiang; E, Mile; F, Chenghai; G, Chuxiong; H, Pudu; I, Yimen. Shot-point designations are two-letter codes: ER, Eryuan; XY, Xiangyun; CH, Chuxiong; JC, Jiangchuan; BI, Bingchuan; XG, Xiaguan; BA, Baoshan; ZH, Zhefang; SI, Simao; YU, Yuanjiang; JI, Jincheng; MA, Malong. Small and large open circles are epicenters of historic earthquakes in the magnitude range 6 to 7 and greater than 7, respectively.

Fieldwork was conducted during November and December 1982. High-quality data were obtained on lines 1 and 2. On line 3, however, poor coupling of the explosions into the ground at two of the four shot points seriously degraded data quality beyond 20 to 30 km, limiting the deeper crustal information. The interpretation presented here pertains to lines 1 and 2 only.

Interpretation of seismic refraction profiles begins with the identification of the discrete arrivals (phases) of seismic waves on the composite 196-trace record sections derived from each shot. Depending on the distribution of velocities and interfaces of acoustic impedance contrast within the earth's crust (that is, the velocity structure), the phases may reach the sensor at a given location along the profile by several possible direct, reflected, and refracted paths. Arrival times as well as amplitudes are determined by the velocity structure, and interpretation consists of finding a velocity structure that best predicts the observed seismic record sections. In regions with complex, laterally varying structure, interpretation usually begins with one-dimensional (horizontally layered) models at each shot point, with subsequent incorporation of lateral variations through numerical modeling of times and amplitudes in two-dimensional structures. Ray tracing in one dimension was accomplished with an algorithm that operates on a model consisting of a series of layers, each with positive or negative gradients, by analytically solving for the travel time in each layer. Two-dimensional modeling was accomplished according to an algorithm that shoots rays through the model with a Runge-Kutta integration scheme (*13*). The Yunnan profiles have been analyzed in such fashion.

The record section, calculated travel-time curve, and velocity-depth model for the profile from Eryuan southeast (Fig. 1) are shown in Fig. 2, A and E; the velocity model is given in Table 1.

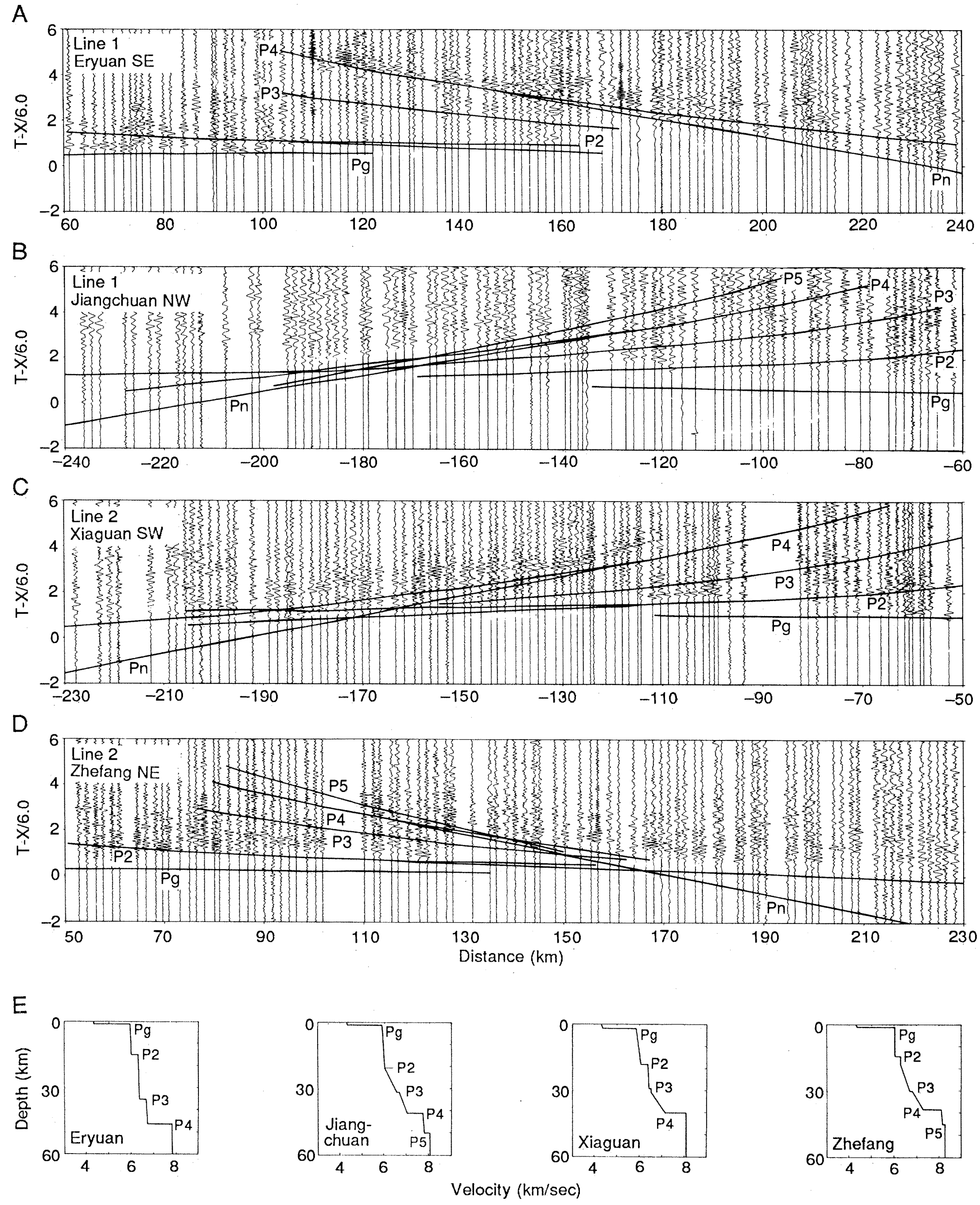

Fig. 2. Seismic record sections and velocity-depth models, with calculated travel-time curves superposed on sections for (A) Eryuan southeast, (B) Jiangchuan northwest, (C) Xiaguan southwest, and (D) Zhefang northeast. Travel times (T-X/6.0) are reduced to 6.0 km sec^{-1}. (E) One-dimensional velocity-depth models for the four profiles. Symbols Pg, P2, and so forth designate the velocity discontinuities in (E) and associated seismic wave travel times in (A–D).

Table 1. Velocity-depth functions for the profiles in Fig. 2. Centered numbers indicate the bottom of the models.

Eryuan southeast		Jiangchuan northwest		Xiaguan southwest		Zhefang northeast	
Depth (km)	Velocity (km sec^{-1})	Depth (km)	Velocity (km sec^{-1})	Depth (km)	Velocity (km sec^{-1})	Depth (km)	Velocity (km sec^{-1})
0.0 – 1.25	4.3 –4.33	0.0 – 1.25	4.3 –4.33	0.0 – 1.85	4.3 –4.35	0.0 – 1.12	4.3 –4.35
1.25–15.0	5.95–6.0	1.25–20.5	5.9 –6.0	1.85–18.2	5.85–6.07	1.12–14.3	6.0 –6.1
15.0 –35.0	6.3 –6.35	31.5 –31.5	6.55–6.65	18.2 –29.1	6.38–6.42	14.3 –18.0	6.28–6.32
35.0 –46.3	6.65–6.7	41.0 –41.0	7.0 –7.7	29.1 –30.58	6.48–6.5	30.0 –30.0	6.7 –6.8
46.3 –60.0	7.75–7.8	52.0 –52.0	7.75–8.0	40.1 –40.1	7.15–8.06	38.5 –38.5	7.3 –8.1
		60.0	8.1	60.0	8.1	45.0 –45.0	8.15–8.25
						60.0	8.3

Below the surficial layer, the upper crust has a velocity of 6.0 km sec^{-1}. Two intracrustal boundaries, at depths of 15 and 35 km, separate layers with velocities of 6.0 and 6.3 km sec^{-1} (the boundary labeled P2), and layers of 6.3 and 6.6 km sec^{-1} velocities (P3). The strong reflection from the crust-mantle boundary (P4) indicates a crustal thickness of 46.5 km. The apparent velocity of the mantle refraction (P_n) is 7.75 km sec^{-1}. The record section and velocity-depth model for the reversing shot point, Jiangchuan northwest, is shown in Fig. 2, B and E. The crustal thickness is 41 km, and here also an apparent velocity of 7.75 km sec^{-1} is observed for the upper mantle P_n phase. The two 7.75 P_n velocities indicate that the upper mantle has an anomalously low velocity. There is some evidence for a reflected phase from within the upper mantle (P5).

The record section and velocity-depth model for the profile from Xiaguan southwest is shown in Fig. 2, C and E, and the velocity-depth model is given in Table 1. The average velocity of the upper crust is slightly less than 6.0 km sec^{-1}, that of the middle crust is 6.4 km sec^{-1}, and the lower crust is modeled with a gradient from 6.5 to 7.1 km sec^{-1}. The total crustal thickness is 40 km. The calculated velocities and depths are well constrained by the very clear, high-amplitude wide-angle reflections from the P2 and P4 boundaries. The apparent velocity of the upper mantle refraction is 8.05 km sec^{-1}. The record section and velocity model for the reversing shot point, Zhefang northeast, is shown in Fig. 2, D and E. The total crustal thickness is 38.5 km, and the P_n velocity of 8.15 km sec^{-1} indicates that the true velocity of the upper mantle between these shot points is about 8.1 km sec^{-1}. There is also some evidence for a reflected phase from the upper mantle (P5) on this profile.

Cross sections of the crust along lines 1 and 2 were constructed by combining the one-dimensional velocity-depth models for the four shot points on each line and then adjusting boundary depths on the basis of clear reflected and refracted arrivals. To do so, individual reflected (or refracted) arrivals are plotted at their bottoming point (or critical refraction takeoff point) by using the average velocity structure above the reflection point (or along the refracting horizon). The average velocity structure is taken from the results of one-dimensional modeling. As a final step, the cross sections served as input to a two-dimensional ray-tracing program, and velocities and layer boundaries were adjusted to achieve a travel-time fit of ±0.1 second.

Some significant lateral variations in velocity structure are evident in the fence-diagram presentation of the two crustal cross sections (Fig. 3). Along line 1, the upper crustal boundary (P2) varies in depth from 13 to 22 km, with the deeper values to the southeast. Where lines 1 and 2 intersect near Xiaguan, the depth to this boundary differs by 4 km, the greater depth being on line 2. If we

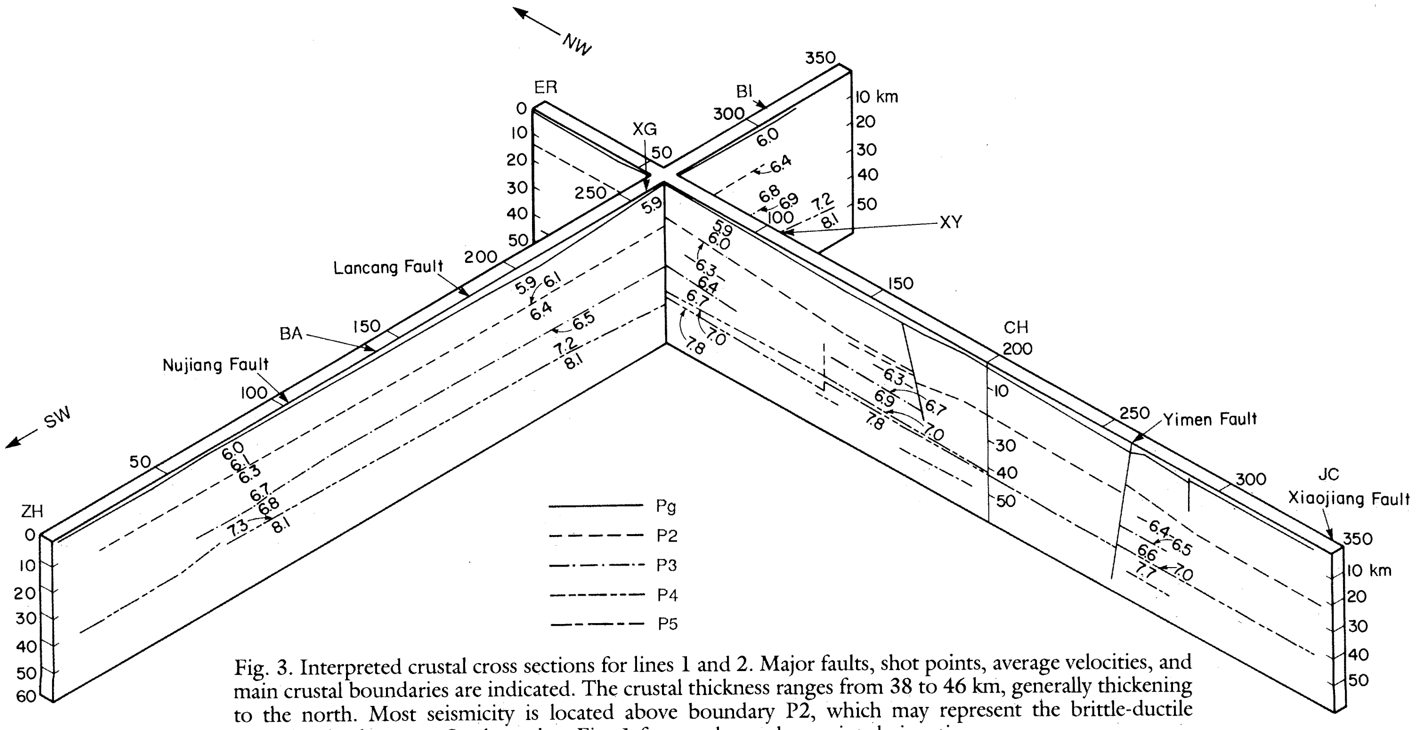

Fig. 3. Interpreted crustal cross sections for lines 1 and 2. Major faults, shot points, average velocities, and main crustal boundaries are indicated. The crustal thickness ranges from 38 to 46 km, generally thickening to the north. Most seismicity is located above boundary P2, which may represent the brittle-ductile transition in the crust. See legend to Fig. 1 for two-letter shot-point designations.

assume that the two lines recorded arrivals from the same boundary, the discrepancy in calculated depth indicates that unmodeled lateral-velocity variations occur near the crossing point of the two lines. (An additional factor contributing to this discrepancy is the crookedness of the two lines, which follow available access routes.)

The depth to the lower crustal boundary (P3) is fairly consistent at 31 to 32 km along line 1, but the velocity contrast across the boundary decreases from 0.3 to 0.1 km sec^{-1} to the southeast. The total crustal thickness varies from 39 to 46 km, with the greatest thickness to the northwest, near Eryuan. Some 5 km of the increase in crustal thickness seems to occur near the two main faults along the line. One step occurs at the Yimen fault (a 2-km offset, down to the northwest), and the other occurs about 20 km southeast of the Xiangyun shot point (3-km offset, down to the northwest). The latter step may be associated with the northwest-southeast trending Chuxiong fault zone, along which line 1 was recorded.

There seem to be few abrupt lateral variations in structure along line 2. This is surprising in light of the major normal faults (*1*) crossed by the line. The depths to both intracrustal boundaries increase somewhat to the northeast toward Binchuan. The P2 boundary increases in depth from 14 to 17 km, and the P3 boundary increases from 30 to 32 km. Southwest of Xiaguan the crust is 39 to 40 km thick, and to the northeast, near Binchuan, it is 45 to 46 km thick. The increase in crustal thickness may occur as a rapid change or in a step near Xiaguan, possibly associated with the Red River fault. No evidence exists at present for a pronounced change in velocity structure across the Red River fault, even though the rocks on either side are reported to have different geologic histories (*14*). Nor does line 2 appear to have a travel-time delay in the shallow crustal phases that could be due to low-velocity fault gouge, as is observed along portions of the San Andreas fault system of California (*15–17*).

A major difference between the two lines is the upper-mantle velocity—7.75 km sec^{-1} on line 1 and 8.1 km sec^{-1} on line 2. In addition, three of the record sections on line 1 give evidence for an upper-mantle reflection coming from 48- to 50-km depth (P5), and one record section on line 2 shows a similar phase.

Seismic refraction measurements in Yunnan Province have been interpreted to show a 38- to 46-km-thick crust that can be described as three layers with average velocities of 6.0, 6.3, and 6.6 to 6.8 km sec^{-1}. This average crustal structure is similar to that of continental platforms, such as the north China plain (*18*) and the Turanian and Russian platforms (*19, 20*). The upper two layers extend to a depth of 30 to 35 km, yielding a thick section of crust with low average seismic velocity. The velocities in this upper section are consistent with a crustal composition of meta-sedimentary and silicic intrusive rocks, but mafic rocks must constitute a low percentage of the section (*21*). The seismic velocities found in the lower crust are consistent with high-grade metamorphic rocks, but they are inconsistent with mafic rocks, which would have higher velocities at such depths. Thus, there is no evidence in the seismic velocities that this region has been formed through the accretion of mafic oceanic crust, as has been suggested (*22, 23*). Additional geological and paleomagnetic evidence is necessary to place additional constraints on the evolution of the crust in this region.

The crust of western Yunnan is currently undergoing strong deformation as a result of the Himalayan orogeny. The crust is thickened to the north (*2, 12*), but the thickness is much less than the 50- to 70-km values determined in a recent Sino-French investigation of the Tibetan plateau (*24, 25*). This northward trend of crustal thickening from Yunnan to Tibet is generally consistent with crustal isopach maps developed from gravity data (*12*).

A major difference from the structure of continental platforms is the low (7.75 km sec^{-1}) upper-mantle velocity measured on line 1. There are several possible explanations for this observation. Line 1 was recorded largely along the Chuxiong fault, which currently has a higher level of seismicity southeast of Xiaguan than the geologically more prominent Red River fault. The low upper-mantle velocity may be due to the upwelling of asthenospheric material along a lithospheric fracture; however, we know of no similar observation along any other major strike-slip fault. Alternatively, the low velocity on line 1 [and the corresponding higher velocity (8.1 km sec^{-1}) measured on line 2] may be due to strain-induced anisotropy (*26, 27*). A third possibility is a difference in subcrustal lithospheric properties near the Red River fault zone. The second alternative, strain-induced anisotropy, appears to be the most likely explanation. The completion of a planned 700-km north-south line at the longitude of Xiaguan will provide additional information on the variation of crustal properties and the possible azimuthal dependence of the upper-mantle velocity.

The determination of the relation between crustal structure and seismicity is an important goal of this investigation. The maximum depth of seismicity seems to correspond to the depth of the P2 boundary; both occur at about 15 km over most of the region, although focal depths have large uncertainties. Since this boundary is evidenced by strong wide-angle reflections, it may represent an important change in average crustal properties, such as composition or grade of metamorphism. We suggest that this boundary also corresponds to the brittle-ductile transition in the crust, below which seismicity is sparse, as in other regions of China (*28*). This hypothesis and other seismotectonic ideas concerning Yunnan Province may be tested more rigorously with the new crustal velocity structure presented here, which will improve accuracy in determining earthquake locations and source parameters.

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