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Oblique Convergence in the Himalayas of Western Nepal Deduced from Preliminary Results of GPS Measurements

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Abstract. A GPS network consisting of 29 sites was installed in central and western Nepal, with measurements taken in 1995 and partial remeasurements in 1997. Data suggest 15 +/- 5 mm/yr of N180° convergence between the Higher Himalayas and India, a result that is consistent with N-S shortening across the arcuate shape of the Nepalese Himalayas and an oblique underthrusting of the Indian crust below the High Himalayas of western Nepal. A 4 +/-3 mm/year E-W extension and deviation of the principal shortening axes are inferred east of 83°E, where Quaternary faults (Darma-Bari Gad fault system and Thakkhola graben) delineate a crustal wedge. This wedge is located on the SE projection of the Karakorum fault and may segment the Himalayan thrust belt. The convergence between the outer belt of western Nepal and India is less than 3 mm/yr, an attenuation consistent with creep on a dislocation locked beneath the Lesser Himalayas. A preliminary model suggests that this N120°E striking dislocation is affected by a 19 mm/yr thrust component and a 7 mm/yr right lateral component.

Introduction

A GPS network of 29 benchmarks was installed in western Nepal to evaluate the convergence rate in the Himalayas and the slip deficit in the seismic gap between magnitude >8 earthquakes that occurred during the last century in the Himalayas [Molnar, 1987 ; Bilham et al., 1995]. This network was measured in 1995 (IDYLHIM project) and includes points common to the 1991/1992 CIRES network [Bilham et al., 1997]. Repeat measurements of 10 IDYLHIM points were taken in 1997. This paper presents the velocities and deformation pattern deduced from this dense network.

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Regional Background

Structural and neotectonic pattern of western Nepal

Quaternary faulting in western Nepal occurred along the thrust splay of the Siwaliks or has reactivated major faults [Nakata, 1989] such as the Main Boundary Thrust (MBT). The direction of motion along the active thrust splay is nearly perpendicular to the trend of the belt and the convergence rate in the Outer belt south of MBT, deduced from the uplift of Holocene terraces, is of the order of 18 +/- 4 mm/year in western Nepal [Leturmy, 1997], and 21.5 +/- 2.5 mm/year in central Nepal [Lavé and Avouac, 1998]. Late Quaternary motion along MBT is characterised by right-lateral and down to the north motion. The best expressed late Quaternary faulting in the Lesser and Higher Himalayas extends from the Bari Gad fault to the Darma fault [Nakata, 1989; Yeats and Lillie, 1991] and is on the S.E. projection of the right lateral Karakorum Fault zone (KF). The Bari Gad and the Darma faults have the same characteristics as the KF zone [Nakata, 1989]. The slip rate across the KF, which is a major fault accommodating lateral extrusion of Tibet [Avouac and Tapponnier, 1993], decreases eastward [Liu, 1993]. The eastward prolongation of the KF is still under discussion. It is believed that the KF can be traced into and across Nepal and South of the Himalayas in Ganga-Brahmaputra delta [Nakata, 1989] or is connected with the Jiali fault in Tibet [Armijo et al., 1989]. The extension of southern Tibet locally affects the Higher Himalayas at the boundary between western and central Nepal (Thakkhola graben).

Seismicity

The underthrusting of India under the Himalayas causes magnitude >8 earthquakes [Molnar, 1987], nevertheless a 500 to 800 km long segment between the locations of the huge 1934 Bihar-Nepal and the 1905 Kangra earthquakes has not experienced a major tremor for more than two centuries [Bilham et al., 1995]. Events with magnitude between 5.5 and 7 have been recorded in the Himalayan-Tibet area (Fig. 1). Their focal mechanisms suggest: (1) extension in south Tibet and (2) a shallow (10-20 km focal depth) décollement beneath the Lesser Himalayas gently dipping to the north [CMT Harvard, 1998]. In central and western Nepal, intense microseismicity and frequent medium-size earthquakes (ML<4) tend to cluster in front of the Higher Himalayas [Pandey et al., in press] whereas in eastern Nepal, microseismicity extends farther south (Fig. 1). This microseismic activity is interpreted to reflect the stress build-up in the interseismic period, during which the décollement beneath the Lesser Himalayas would remain locked [Pandey et al., 1995 ; Bilham et al., 1997] while aseismic creep would be located beneath the Higher Himalayas. It is thus inferred that the microseismic belt that follows the front of the High Himalayas in central and western Nepal (Fig. 1) marks the southern tipline of the zone of aseismic slip beneath the High Himalayas.

Idylhim Gps Survey

Network setting

The IDYLHIM GPS network (Fig. 2) is focused on the deformation pattern above the Himalayan detachment and the dense network installed in the Siwaliks of the outer Himalayas has been designed to evaluate aseismic creep along the frontal set of Quaternary thrusts, as inferred in central Nepal by Jackson and Bilham [1994]. The sites are materialized permanently.

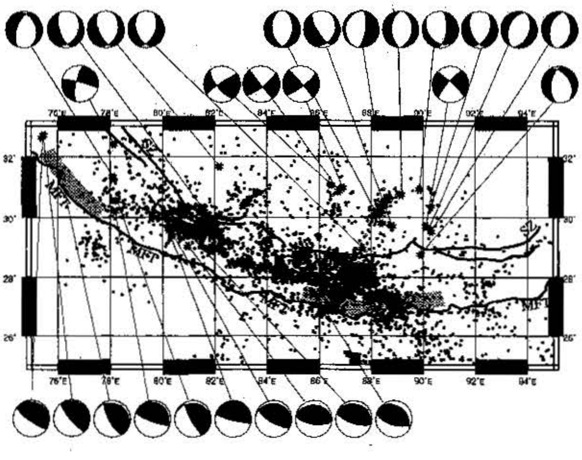

Fig. 1: Seismotectonic map of central Himalayas. Epicenters of earthquakes from Pandey et al. (1998) are shown by empty circles. Focal mechanisms of 1977-1998 earthquakes (depth < 25 km) from CMT catalog. MFT, SZ and KF are respectively Main Frontal Thrust, Suture Zone and Karakorum Fault.

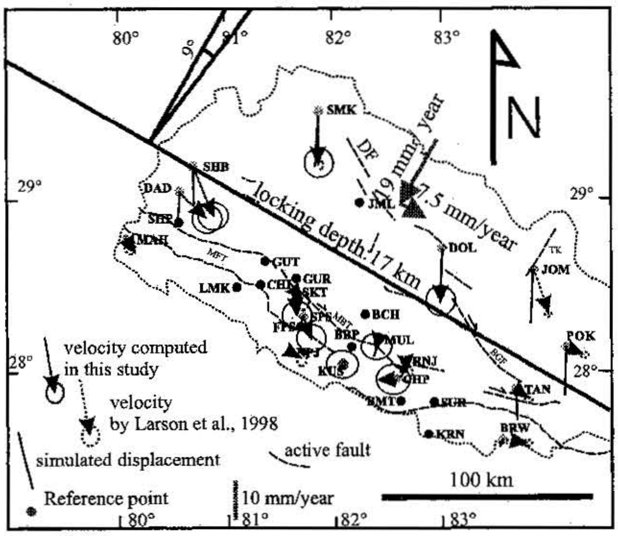

Fig. 2: Horizontal displacement between GPS point and a reference point at the front of the belt (KUS) with 1σ uncertainties, and comparison with displacements simulated by a single dislocation model. DF, BGF, TK, MBT and MFT are respectively Darma Fault, Bari Gad Fault, Thakkhola graben, Main Boundary Thrust and Main Frontal Thrust.

Acquisition and processing of data

The measurements in 1995 and 1997 were taken with Ashtech dual-frequency receivers. In 1995, each benchmark was measured with codeless or Z code receivers for at least three 12 hour night sessions and in some cases with three 24-hour sessions, the points SKT and SMK were measured throughout the survey (15 days). In 1997, all the points were measured with Z code receivers for at least three 24-hour sessions, the point SKA0 was measured throughout the survey. The data were analysed with the Bernese V4.0 software in the ITRF94 reference frame using IGS precise orbits, IGS Earth Orientation Parameters, satellite clock error files, and data from 7 IGS stations (TAIW, LHAS, IISC, POL2, KIT3, IRKT, SHAO). The data analysis was performed using the QIF strategy of resolution [Beutler et al., 1996]. This strategy allows codeless and Z code receivers to be combined in a single run. To increase the vertical component accuracy, the local troposphere was estimated using an elevation-dependent observation weighting model. In 1995 more than 60-70% of the carrier phase ambiguities were fixed, against only 50% in 1997. The mean repeatabilities of north-south and east-west components of the baselines are respectively 2 and 3 mm for 1995, and 1.5 and 3 mm for 1997. For each survey, one normal equation was obtained by the stacking of normal equations constrained to agree with the ITRF94 reference frame.

Results

The 1995/1997 velocities, were obtained by the addition of the normal equations of these surveys. In a second stage, the velocities defined in the ITRF94 reference frame were expressed with reference to the point KUS. Uncertainties on velocity depend on the repeatability of the position estimate, the time span between the two measurements and a time correlated error. The time corellated error cannot be estimated in the lack of permanent GPS measurement in the western Nepal but following Dixon et al., 1998, it is intended to use the global trended unfiltered time series from the permanent station that may be representative of the network conditions. As most of the network is located in the Siwaliks, it was preferable to use the data from Bangalore (Sopac unfiltered time series) in India to estimate the time-correlated noise. The uncertainties concerning velocities are estimated with two terms added squaring the short term uncertainties plus time-correlated uncertainties estimated with IISC data. The estimate of CIRES point velocity, shown by dotted ellipses (Fig. 2), has been improved by using new data from Larson et al. (submitted) computed in the ITRF94 reference frame with the same IGS stations as in our study. The two sets of velocities, which contain nine common points (7 IGS stations, SMK and SKT) both expressed in the ITRF94 reference frame, have been compiled by considering point SMK as reference and finally drawn by reference to point KUS. A 15 +/-5 mm/year N180°E velocity is found for the points of the Higher Himalayas of far-western Nepal (SMK and DOL), and 12 +/- 3 mm/year N165° velocity for JOM. The extension rate parallel to the chain in the Higher Himalayas (i.e. between DOL and JOM) is 4.5 +/- 3.5 mm/yr. Strain rate tensors (Fig. 3) show that the principal shortening axes change from a N15-25°E trend in far-western Nepal to N160-165°E in western and central Nepal. Extension is only found in the triangles east of 82°30'E (TAN-JOM-RNJ: +0.03 μstrain/year; JOM-POK-TAN: +0.06 μstrain/year; TAN-BRW-POK: +0.16 μstrain/year). Displacement of the points in the vicinity of MBT is generally in the range of the noise (i.e. less than 3 mm/year), though SPS displacements exceed the 1 σ level uncertainties (6+/-5 mm/year). The strain rate tensors for the Siwaliks zone (Fig. 3), which are not supported by a high confidence level, are only suggestions.

Seismotectonic Interpretation

Simulation of the present-day velocity field

An interseismic strain accumulation has already been suggested for central and eastern Nepal [Pandey et al., 1995; Bilham et al., 1997]. This assumption is tested in western

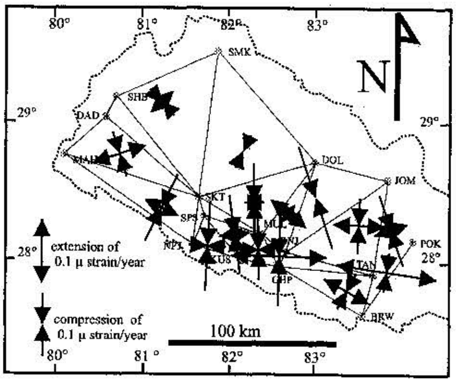

Fig. 3: Strain rate tensors deduced from GPS measurement.

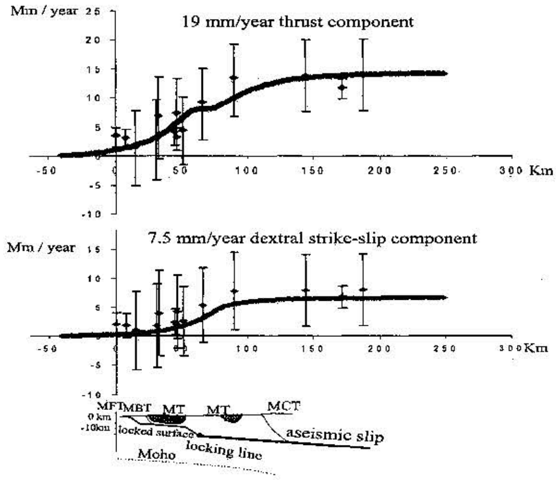

Fig. 4: Simplified cross section through western Nepal.Thrust and strike-slip components measured in western Nepal are compared with those simulated with a dislocation model dipping 9° north-eastward and that creeps by a 20.5 mm/year in a N-S direction. MCT, MT, MBT and MFT are respectively Main Central Thrust, Mahabarat Thrust, Main Boundary Thrust and Main Frontal Thrust.

Nepal by using a dislocation model where a buried planar thrust fault surface is locked at its southern tip and affected by a uniform aseismic creep [Okada, 1985]. This dislocation approximates ductile deformation of the lower crust, and its tip is interpreted as either a flat-ramp connection or as a ductile-brittle transition. The strike of the dislocation is assumed parallel to the average structural direction (Fig. 1) and to the direction of the seismicity band of far-western Nepal; i.e. near N 120°E. The 1995/1997 velocities from our network and the 1991/1997 velocities estimated by Larson et al. (submitted) in western Nepal are used to constrain the simulation. In the eastern area, a 3D complexity is linked to a line parallel to the chain extension that could be explained by deformation along the Thakkhola fault or along the Bari Gad Fault system. The influence of these faults and therefore the velocities of JOM, POK, TAN and BRW will be excluded from the simulation. The solution that minimises the differences between simulated and observed velocities is obtained for a N 120° planar dislocation dipping 9° northward, with a locking depth at 17 km below the Lesser Himalayas. It creeps by 20.5 mm/year in a N-S direction, corresponding to a 19 mm/year thrust component and a 7.5 mm/year dextral strike-slip component (Fig. 2 and 4). The distribution of earthquakes of magnitudes over 5.5, just above or north of the locked-unlocked limit, is consistent with a stress accumulation in the interseismic period [Pandey et al., 1995], whereas slip vectors deduced from their focal mechanisms vary from N180°E to N210°E (Fig. 1).

Comparison between present-day deformation and neotectonics of the Himalayas

The 20.5 mm/year oblique slip along a planar dislocation locked frontally accounts for a correct approximation of the surface velocity field in the zone where the strain rate tensors do not show extension perpendicular to the principal shortening direction. This deep-seated oblique slip agrees with oblique convergence in the Himalayas and southern Tibet plateau (McCaffrey and Nabelek, 1998) and with the displacement partitioning observed along the active Quaternary faults of the outer belt of western Nepal, i.e. dextral slip along the steep MBT and a long-term 18 mm/year pure thrusting along the active frontal faults of the Siwaliks. The dextral strike-slip along the MBT results from the non-orthogonality between the convergence vector (NS) and the direction of the structures (N120°). Because of the curvature of the arc, the deviation from orthogonality vanishes eastwards, and so does the amount of strike-slip. The agreement of these long-term contraction rates across the frontal part of the Himalayan thrust system, and the aseismic slip rate simulated below the higher Himalayas, suggests that detachment slip episodically accommodates most of the contraction. The 3-6 mm/year difference between the observed and the simulated displacement of SPS gives a maximum for the contribution of small earthquakes or plastic strain north of the MFT and most of the slip presumably occurs in major Himalayan detachment earthquakes. Between 83°E and 84°E, the present-day deformation field is characterised by obliquity between the trend of the belt and the principal shortening direction (Fig. 3) and by extension perpendicular to this shortening. This area appears as a major transition: 1) in the high relief distribution (the >8000 m peaks are located east of 83°30), 2) in the microseism distribution, 3) in the location of Quaternary faulting in the Lesser and the Higher Himalayas. The Darma-Bari Gad fault system and the western border of the Thakkhola graben roughly delineate a crustal wedge, related to the horse-tail termination of the Karakorum fault system. These faults would be located at the transition between two different segments of the Himalayan detachment above the Indian crust.

Conclusion

The agreement of our preliminary results with other geological and geophysical evidences suggests that: 1) the present-day deformation of the Himalayas of western Nepal may be described approximately as that induced by an oblique convergence along a north dipping creeping dislocation that extends beneath the Higher Himalayas and southern Tibet. The stress build-up zone at the southern edge of the dislocation would appear to coincide with the belt of microseismic activity that follows the front of the Higher Himalayas across Nepal. Oblique thrusting in western Nepal is partly the result of the arcuate shape of the Himalayas; 2) between western and central Nepal, the Himalayas are affected by a more complex kinematic pattern characterised by rotation of the principal strain axes transverse to the extension of the range. It is suggested that faults linked to the lateral extrusion of Tibet (such as the end of the Karakorum fault or the Thakkhola structures) also affect the High Himalayas, which act locally as an oblique collisional orogeny. The kinematics and seismotectonics of western Nepal appear to be slightly different from those of central Nepal.

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