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DOSE Grant NAG5-1941: "Application of Global Positioning Measurements to Continental Collision in the Pamir-Tien Shan region, Central Asia"
Principal Investigators: Michael W. Hamburger and Robert E. Reilinger

DOSE Grant NAG5-1947: "GPS Survey of the Western Tien Shan"
Principal Investigators: Bradford H. Hager and Peter Molnar

In this report, we summarize what we have accomplished with five years of funding from NASA under its DOSE program, and with a comparable level of funding from NSF. We describe the development of a GPS network in the Tien Shan of Kyrgyzstan and Kazakhstan of the former Soviet Union, the analysis of data, and the main results. This discussion presents the state of the current network, which has grown significantly since the termination of our DOSE grants, with continued support both from NSF through its continental dynamics program and from NASA's SENH program. Although grants from NASA's DOSE program did not support this growth not directly, it did so indirectly by building the infrastructure that has enabled further expansion in an area where otherwise there would be only a small GPS presence. We note how the network has grown over time, but the emphasis of this discussion is on the quantity and quality of measurements that we have made.

Let us emphasize three points developed below:

In terms of number of sites, density of sites, number of continuous sites, and number of repeated measurements, our network (Figure 1) may rank third in the world: less dense and less well surveyed than those in southern California and Japan, but comparable in size, density of benchmarks, and frequency or repeated surveys, to networks in Italy, Greece, and Turkey, and far denser and better surveyed than any in the rest of Asia.

We have developed an excellent relationship with our local collaborators that has made our study both a test of and the measure of success of the "multi-modal occupation strategy" ("MOST"); our colleagues now take responsibility for GPS field campaigns, make all measurements with instruments using equipment on long-term loan from the UNAVCO/NASA instrument pool, and continually expand the network by adding and measuring new benchmarks. They also maintain continuously recording stations and actively process GPS data.

Our measured rate of deformation across the Tien Shan is roughly twice what we expected and what had been predicted by others. Hence, we are studying a more active region than we anticipated, and the average signal-to-noise ratio of deformation is double what we expected. This high rate has obvious implications for understanding and evaluating earthquake hazards.

Development of the GPS Network

When we sought funding to carry out GPS work in Central Asia, we proposed to install roughly 60 sites and measure them twice, in 1993 and 1995 before the DOSE program ended in 1996. Our network currently includes more than 300 sites, *excluding* recovery marks (Figure 1). Among these sites, we record continuously at seven, and our colleagues soon will be installing two more such stations (Table 1).

We measured a pilot network of 13 sites in 1992 and then expanded that network to 86 sites in 1993. This 86-site network includes 14 sites of another regional network installed by our colleagues in collaboration with the GeoforschungsZentrum (GFZ) in Potsdam, Germany. We remeasured 35 of the 86 sites 1993, the whole network four times (1993, 1995 twice, and 1996), and much of it again in 1997. In 1995, our colleagues at the Electromagnetic Field Expedition from the Institute of High Temperatures or the Russian Academy of Sciences (IVTRAN: located near Bishkek, Kyrgyzstan) installed another 46 sites across the Tien Shan, and they have measured them annually (1995, 1996, and 1997). Our collaborators from the Kyrgyz and Kazakh geodetic agencies (Kyrgyzgeodeziya and Kazgeodeziya) installed another 46 sites, including dense monitoring networks near the capital cities of Bishkek and Almaty. In late 1996, our colleagues from IVTAN installed a local 25-site network just south of Bishkek, capital city of Kyrgyzstan, linked to three continuously recording stations in the vicinity. Monthly measurement of this network has just begun, and is expected to continue on a year-round basis with support from the SENH program. In 1997, with NSF support, we installed another 28 sites to fill in holes in the network, where sparse coverage of the GFZ network left holes; these new sites have been measured twice in 1997. Finally, later in the summer of 1997, our colleagues at IVTRAN installed yet another 73 sites in the eastern part of the Tien Shan in Kyrgyzstan, as part of the NSF program in Continental Dynamics. In addition to the measurements at these principal geodetic sites, our colleagues at IVTAN have installed 2-3 recovery (reference or security) benchmarks surrounding each of the GPS network stations at distances of a few to tens of meters. These recovery marks will ensure security of the network if the main marks are damaged, and will permit local studies of benchmark stability in case of anomalous crustal motions at these sites. We hope that readers of this report will see that we have made nearly an order of magnitude more measurements than were originally planned.

The success of this work has depended on a number of fortuitous circumstances.

First, as noted above, virtually all of the field work was accomplished by our colleagues at IVTRAN, Kyrgyzgeodeziya (the Main Administration for Geodesy and Cartography in Kyrgyzstan), and Kazgeodeziya (the Main Administration for Geodesy and Cartography in Kazakhstan). In particular, our main collaborator, Yuri A. Trapeznikov of IVTRAN, has organized much of the field work and taken responsibility for the maintenance of both the most reliable continuously recording station (POL2) and nearly all of those currently operating. He masterminded the installation of most of the network, of now more than 300 sites. In 1993, he orchestrated 18 field vehicles, each with a crew, in the first measurement of the 86-site network. Subsequently, he organized the systematic installation of recovery marks at nearly all sites. Toward this end, he designed a special benchmark that can be installed as a buried vertical bolt in the rock. It is easily hidden, but then when surveyed, the antenna can be screwed directly into the bolt. Hence a level antenna is assured, and the height is constant on all subsequent surveys. With such marks, his teams installed another 46 sites in 1995, which they have measured annually since then. He took sole responsibility for installing all but 28 of the ~125 sites installed in the last year. He arranged for 25 sites to be installed along the range front south of Bishkek, which IVTRAN crews will measure every 3-4 weeks to get a long time series. It should be clear that his involvement in the Tien Shan geodynamic project has made this collaborative project a model for other groups employing "MOST" as a strategy for international GPS field projects.

Second, we have received continued support from UNAVCO, both in terms of receivers and field assistance. Field engineers insured success of the campaigns in 1992 and 1993. UNAVCO then loaned receivers for the small campaign in 1994, which had not been budgeted or even scheduled, but seemed feasible given our colleagues' commitment. That small campaign was to be the first real test of MOST. A year later in 1995, again because of the unique development of our network, UNAVCO provided an engineer to oversee the installation of continuously recording stations at three sites. Next, UNAVCO hosted and trained an engineer, Aleksandr Matix, from IVTRAN for 2 months in 1996 to install and maintain continuously recording sites; based on his training at UNAVCO, Matix was also formally certified for repair of the Trimble receivers used in the field campaigns. Because of this training, our program was only a minor burden to UNAVCO in 1997, when one continuously recording station was moved, another five new ones were installed, and two more will be installed shortly. Although a UNAVCO engineer helped make sure that all equipment was shipped safely and promptly to our colleagues, no one from UNAVCO went to the Tien Shan to assist in this work. Thus, we have made a transition from the time when UNAVCO provided field assistance to a time when our colleagues can carry out much of the installation and maintenance.

We have also made the effort to teach our colleagues how to process data, and with funds largely from elsewhere, we have helped them develop the computer capability to carry out this analysis. They routinely process the data that they obtain; we have not, as yet, analyzed the data obtained the 25-site local network just south of Bishkek or 73-site network installed in the summer of 1997 in the eastern part of the Kyrgyz Tien Shan. Preliminary data analysis is currently underway at the IVTAN data processing center in Bishkek.

We have benefited from an exchange of data with scientists of the GeoforschungsZentrum. Their data from stations that we measured have been included in the velocity field shown in Figure 2, the profiles in Figure 3, and the time series in Figure 4. We plan a full exchange of data following their campaign in 1998 and their presentation of those results.

Finally, we should note that continued support from both NASA and NSF has been vital. Support from only one or the other would have been inadequate for us to install and maintain this network, despite the efforts of our colleagues.

Data anlysis and quality

In addition to demonstrating that the "multi-modal occupation strategy" (MOST) enhances data acquisition without increased cost or loss of accuracy, we have taken advantage of the data obtained to develop methods of analysis that can be applied elsewhere. These data offer an ideal opportunity to evaluate the technique of processing subsets of the data separately and merging the results later. Specifically, we have included features in the analysis software that allow different networks (usually a global and a regional network) to be processed separately and then combined to generate results that are nearly equivalent to those that we would have obtained from a simultaneous processing of the combined network. The ability of this analysis scheme to perform such combinations permitted an easy transition from conventional campaign style measurements to those from MOST. Comparison of the repeatability (Table 2) from our full 1993 campaign (18 receivers deployed for 18 days) with our first campaign in 1995 (5 receivers for 30 days) shows no loss of precision with the use of MOST. In fact, presumably because of the improvements in the global tracking network, the RMS scatter of positions has decreased over time, with a big improvement between 1992 and 1993, when that improvement in the calculation of orbits was most significant (Table 2). Moreover, we can now use these features to include the extensive recovery mark data (i.e., marks with in a few tens of meters of our main marks) that have collected since 1995. In fact, because of the much smaller set-up errors associated with the new IVTRAN benchmarks, we now measure the recovery marks, instead of the original marks installed in 1992 and 1993. Finally, we have used these data, especially those from the continuously operating sites, to evaluate and mitigate errors due to multipathing.

Results and their implications for regional tectonics and earthquake hazards

Data obtained from 1992-1997 places a lower bound of 13.3 ± 0.8 mm/yr for the rate of shortening across the Tien Shan (Figures 2-4). Because our network (Figure 1) does not cross the entire range, but stops near the Chinese border, this rate underestimates the total rate across the Tien Shan [Abdrakhmatov et al., 1996]. The high ranges south of our network, in and along the border with China, and their high seismicity attest to active deformation comparable to that where we have worked. In addition, B. C. Burchfiel (from MIT, with separate support from NSF) has mapped a fold-and-thrust belt at the southern edge of the Tien Shan approximately 500 km to the east, and from balanced cross sections, he has estimated an average rate of Quaternary shortening across it of 4.5-14 mm/yr. Thus, our GPS-based estimate surely underestimates the total rate by several mm/yr and suggests that the total rate of shortening across the Tien Shan is ~ 20 mm/yr.

The shortening rate of ~ 20 mm/yr exceeds previous estimates by 50-100%. Seismic moments of earthquakes in this century suggest that shortening occurs at roughly 10 mm/yr, with an uncertainty of as much as a factor of two [Molnar and Deng, 1984]. A preliminary reassessment of the moments by one of us yields smaller uncertainties and an average rate of 10 ± 3 mm/yr. In addition, based (1) on an estimated Holocene shortening rate roughly 1000 km farther east and its extrapolation across the range, and (2) on the greater width of the range in the west, Avouac et al. [1993] inferred a rate of 12 (± 6) mm/yr where we have worked, only 60% of the total rate that we estimate. Shortening across the western Tien Shan at ~ 20 mm/yr accounts for nearly half of India's penetration into Eurasia at 44 mm/yr in this area, despite the Tien Shan's occupying only a modest fraction of the area deformed by India's collision with Eurasia, and despite its great distance from the Himalayan plate boundary. As such, this rate is not a quantity merely of parochial interest to students of Asian kinematics, but bears directly on more general questions of continental dynamics.

Earthquake hazards. The higher rate of convergence (~ 20 mm/yr) than that inferred from seismic moments of earthquakes in this century (~ 10 mm/yr) suggests that great earthquakes may recur more frequently in the Tien Shan than the historic record (the last two centuries) suggests [Abdrakhmatov et al., 1996]. Two earthquakes with M ~ 8 occurred within the Tien Shan in the last century (1815 and 1889) and three in this century (1902, 1906, and 1911). Because the three at the beginning of this century account for the vast majority of the estimated 10-mm/yr convergence rate, contemporary shortening at ~ 20 mm/yr calls attention to the possibility of an imminent major earthquake occurring somewhere in the Tien Shan.

The Tien Shan offers an outstanding laboratory for studying intracontinental tectonics of regions analogous to the Laramide deformation in the Rocky Mountains of the western United States. Perhaps, less appreciated are the tectonic similarities between the Transverse Ranges of southern California, also an intracontinental belt, and the Tien Shan. The major faults in each dip relatively steeply (dips ≈ 30-45°), not at the gentler angles characteristic of subduction zones or of the Himalaya. Deformation is distributed over a finite width, on several faults that bound ranges and basins (the San Fernando Valley resembles basins in the Tien Shan). Because shortening across the Tien Shan seems to occur roughly twice as fast as across the Transverse Ranges, processes occurring in both settings, like earthquake recurrence, can be studied at an accelerated rate in the Tien Shan. Thus, our work contributes not only to understanding the geodynamics of the Tien Shan and its relationship to earthquakes there, but also to an understanding of the same processes responsible for earthquakes in southern California.

Relevance to continental tectonics in general. Our shortening rate allows an estimate of the time scale for deformation in the Tien Shan, and as a result, a correlation with processes occurring at a larger scale [Abdrakhmatov et al., 1996]. Avouac et al. [1993] determined the total shortening across the western Tien Shan in Kyrgyzstan and western China to be ~ 200 ± 30 km. At an average rate of 20 mm/yr, the entire range would have been built in ~ 10 Myr, beginning long after India collided with Eurasia at 50-55 Ma, but at virtually the same time as two changes that relate to the Tibetan Plateau. First, roughly 5-10 Myr ago, the plateau apparently rose rapidly 1-2.5 km, from below its present elevation to perhaps 500 m higher than at present [e.g., Harrison et al., 1992; Molnar et al., 1993]. Second, the Indian monsoon apparently abruptly strengthened ~ 8 Myr ago [e.g., Kroon et al., 1991; Prell et al., 1992]. Our rate of shortening across the Tien Shan relates to these phenomena by corroborating one of the arguments for a rapid rise of the plateau: an abrupt onset of deformation surrounding the plateau suggests an increase in the force applied by a higher plateau to its surroundings. Thus, our rate lends support to the idea that a rapid rise of Tibet perturbed both the circulation of the atmosphere and the hydrologic processes over it that, in turn, strengthened the monsoon.

As active faults bound nearly all ranges and basins within the Tien Shan, deformation must be distributed across the belt. Our measured shortening rate of 13.3 ± 0.8 mm/yr across two thirds of the belt appears include both distributed strain and localized convergence long the northern edge of Issyk-Kul (Figures 2 and 3). A glance at the velocity field (Figure 2) raises additional questions and possibilities: (1) a component of shear strain and/or east-west extension across the interior of the Tien Shan, (2) right-lateral strike slip deformation along the Talas-Ferghana fault, (3) mild, but resolvable, deformation of the Kazakh platform, and (4) a significant strain anomaly in the vicinity of the large Suusamyr earthquake of 1992. As uncertainties in the velocity field decrease, we will pursue these features further.

We are only just beginning to digest these new results. Now that the data have been analyzed, we have begun to prepare papers describing the results. Three such papers have been outlined. One will present the velocity field and will describe the methods that have been used to determine it. A second will interpret that velocity field in terms of the active tectonics and tectonic evolution of the Tien Shan. A third will address transient movements within the Tien Shan in terms of the viscosity structure of the crust and as a general processes associated with active deformation. We anticipate that these papers will be submitted in early 1998.

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Table 1: Continuously recording sites

POL2: 74.694°E, 42.680°N, at the IVTRAN base, just south of Bishkek, and recording continuously since 1995.

CHUM: 74.751°E, 42.999°N, at Chumysh, just NE of Bishkek, installed in 1997. (POL2-Chumysh span the basin in which Bishkek sits.)

KAZA: 73.997°E, 44.208°N, near the town of Kazarman within the Tien Shan SW of Bishkek and east of the Talas-Ferghana fault. Installed in 1997.

KUMT: 78.190°E, 41.864°N, at Kumtor, high in the Tien Shan, south of Issyk Kul. Installed in 1997.

MANA: 72.497°E, 42.493°N, near the Toktogul reservoir. Operated continuously during campaigns in 1995 and 1996.

PODG: 79.483°E, 43.328°N, near Podgorny, Kazakhstan, on the platform north of Bishkek. To be installed in 1997 or 1998.

SELE: 77.017°E, 43.179°N, just south of Almaty, capital city of Kazakhstan. Moved in 1997 from Talgar, where a continuouslly recronding site had operated fro 2 years, to SELE.

SHAS: 75.315°E, 42.621°N, near the village of Shamsi, ~60 km east of POL2, along the same range front that overlooks Bishkek. Installed in 1997.

SUMK: 73.997°E, 44.208°N, ~15 km south of a site of the 85-site netwrok installed in 1993, at Khan Tau, and 300 km north of Bishkek on the stable Kazakh Platform. Installed in 1997.

TALG: 77.327°E, 43.291°N, approximately 30 km east of SELE, operated from 1995 to early 1997, and then moved to SELE.

TSHK: 72.242°E, 41.400°N, near the town of Tash Kumyr, in the Ferghana Basin, and west of the Talas Ferghana fault. To be installed in 1997 or 1998.

Table 2. Root-mean-square differences in repeated baseline vectors

Experiment*	Root-mean-square scatter			# of	Total # of
	N (mm)	E (mm)	U (mm)	Sites	baselines
kaz92	6.0	4.4	19.8	13	140
cats92	3.2	3.1	13.9	12	105
kaz93	2.3	2.3	6.9	82	3276
kaz94	3.5	2.6	8.0	35	492
cats94	2.5	2.1	6.2	13	136
kaz95a	2.4	1.9	6.6	91	1772
kaz95b	2.0	1.7	4.9	64	885
kaz96**	2.2	1.6	5.6	102	2278
kaz97a	2.9	2.5	6.9	38	624

*kaz refers to our surveys, and cats to those by the GFZ.
**The kaz96 survey includes cats96, which was observed at the sametime.

The Total # of baselines is the total number of baseline measurements used in computing the statistics.

Figure 1. Map of our network of GPS sites in the Tien Shan. Stars show sites where continuous recording have been made, with those surrounded by black circles showing those currently recording. The largest star and black circle shows the location of POL2, which has recorded continuously for 3 years now. Yellow circles show sites installed in 1992 or 1993, except those with green triangles in them, which show sites installed in 1997 as part of the NSF Continental Dynamics project. Triangles show sites installed largely by IVTRAN, but also by Kazgeodeziya and Kyrgyzgeodeziya; red triangles indicate those installed in 1995, blue - the 25-site network near Bishkek, and pink - in 1997). Black lines show inferred faults, with triangles pointing in downdip directions for thrust or reverse faulting. The large NW-SW trending black line shows the trace of the Talas-Ferghana fault. Dot-dashed lines follow political boundaries. Shading shows relief, with green areas lowest and brown showing high ridges, but with the highest areas shown by white (where the borders between China, Kazakhstan, and Kyrgyzstan meet).

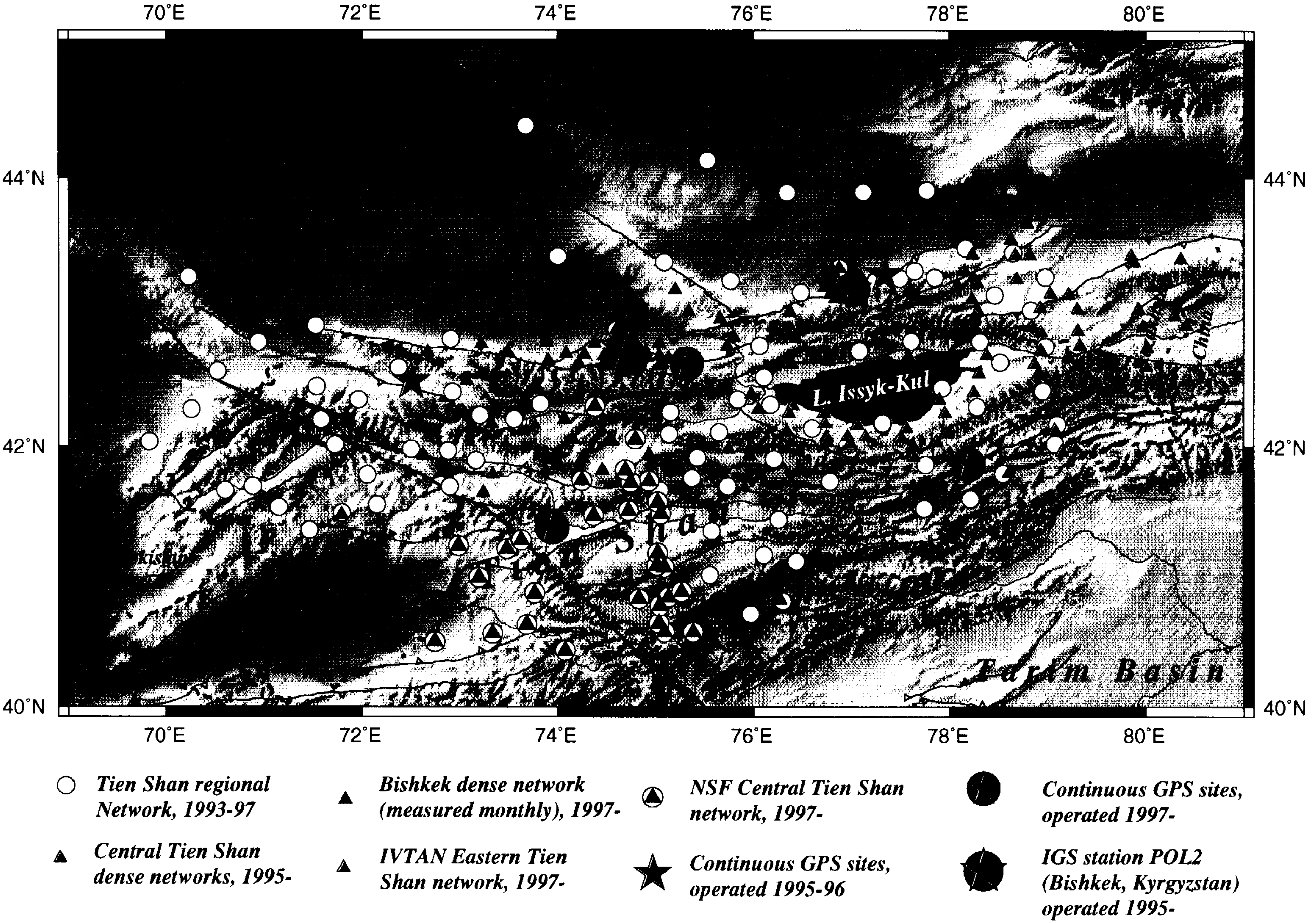
Figure 2. Map of summarizing our results from the remeasurements of GPS sites in the Tien Shan. Red triangles show sites that we installed and measured in 1993, with yellow circles indicating those installed and measured in 1992. Black stars indicate continuously recording sites used in 1995. Arrows show calculated velocities with respect to AZOK. (Arrows emanating from black triangles or without symbols indicates sites installed by IVTRAN and measured sufficiently often to yield resolvable velocities.) Ellipses at the ends of arrows define 95% confidence regions for the velocities. Dot-dashed lines mark political boundaries.

Figure 3. Profiles of north-south components of velocity across the region along four profiles. All velocities are measured with respect to AZOK. Note that, in general, speeds increase southwards, showing N-S convergence across the region, but that there is variability in the profile, which indicates some localized strain, rather than homogeneous strain across the belt.

Figure 4. Time series of changes in estimated north positions of selected frequently observed stations that lie in an approximately north-south profile through AZOK. Each estimate is from the combined analysis of the data from each experiment. (Thus only one estimate per experiment is shown.) The differences between the estimated position and their means (displaced for clarity) in the ITRF94 no-net-rotation frame are shown for AZOK (open squares), ISYK (open triangles) CHOL (closed squares) ARAB (closed triangles) and KULJ (closed circles). See Figure 2 for locations of stations. One standard deviation error bars are shown. The sloping light lines show the velocity estimates from the combined analysis of all data. Note that speeds increase southward and are remarkably constant.

Station	WRMS*	NRMS*	N-S Speed†	N-S Speed‡
AZOK	2.3 mm	1.2	0.3 ± 0.8 mm/yr	1.1 ± 0.6 mm/yr
ISYK	2.5 mm	1.0	3.1 ± 0.9 mm/yr	3.6 ± 0.7 mm/yr
CHOL	2.8 mm	1.7	6.9 ± 0.9 mm/yr	4.8 ± 1.8 mm/yr
ARAB	1.4 mm	0.6	11.1 ± 0.9 mm/yr	10.8 ± 0.6 mm/yr
KULJ	1.7 mm	0.8	13.3 ± 0.8 mm/yr	12.7 ± 0.6 mm/yr

*WRMS: Weighted root-mean-square scatter of postions about the best fitting straight line.
*NRMS: Normalized RMS scatter (square root of chi-squared-per-degree of freedom).
†North-south speed obtained from the combined analysis of all data.
‡North-south speed obtained from fitting the speeds shown, weighted by their uncertainties.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Tien Shan regional Network, 1993-97
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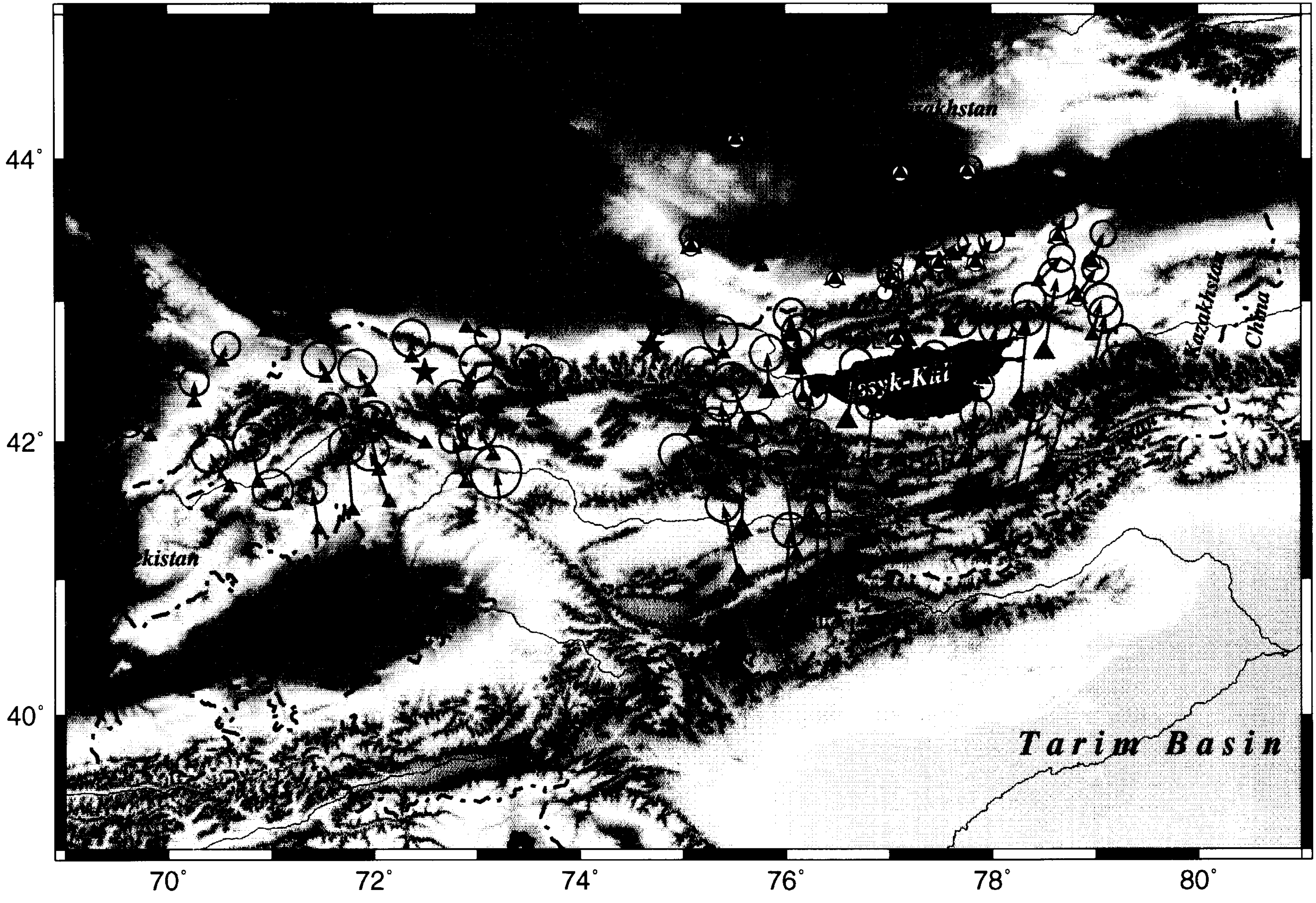
IGS station POL2 (Bishkek, Kyrgyzstan) operated 1995-



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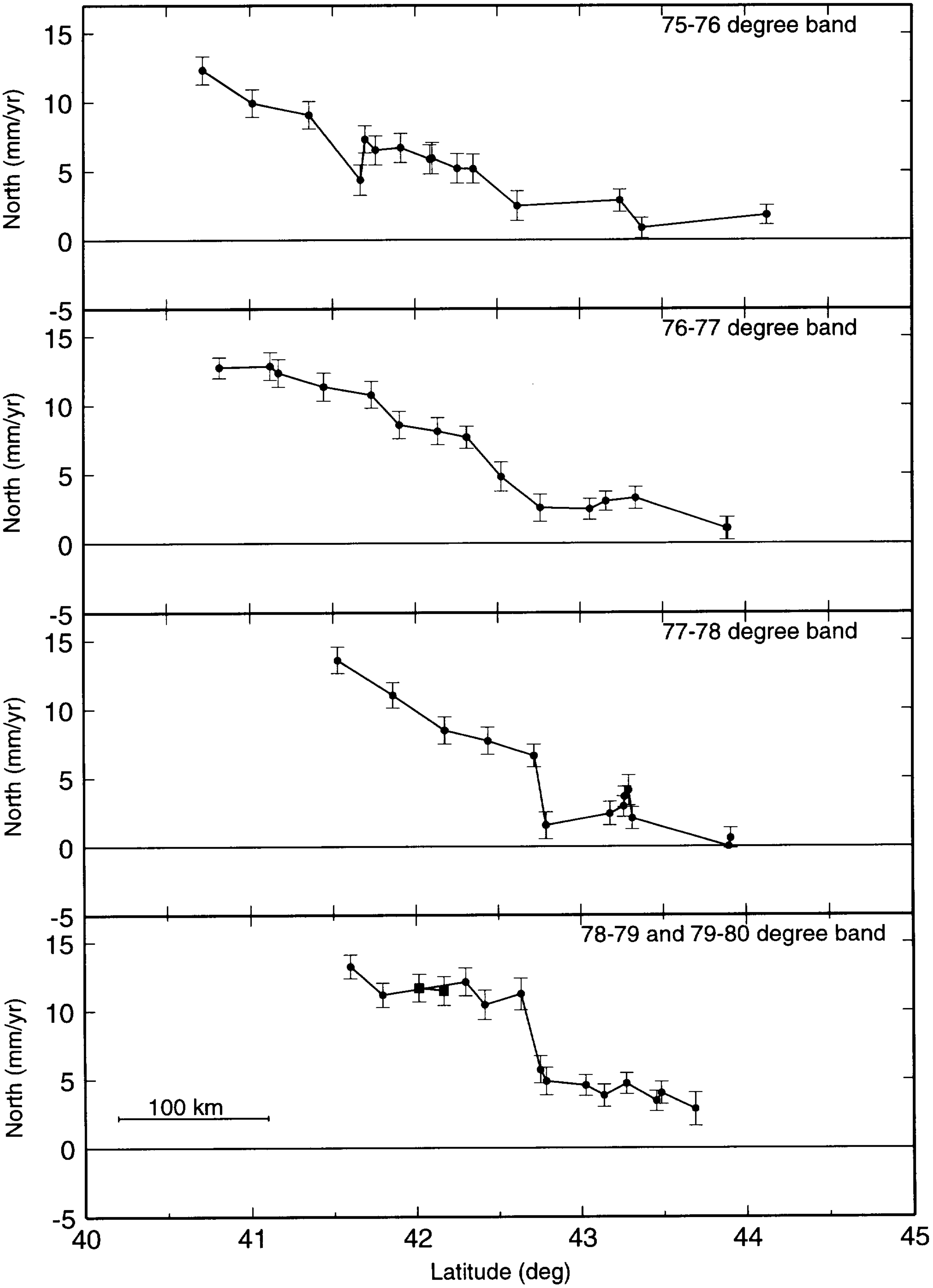
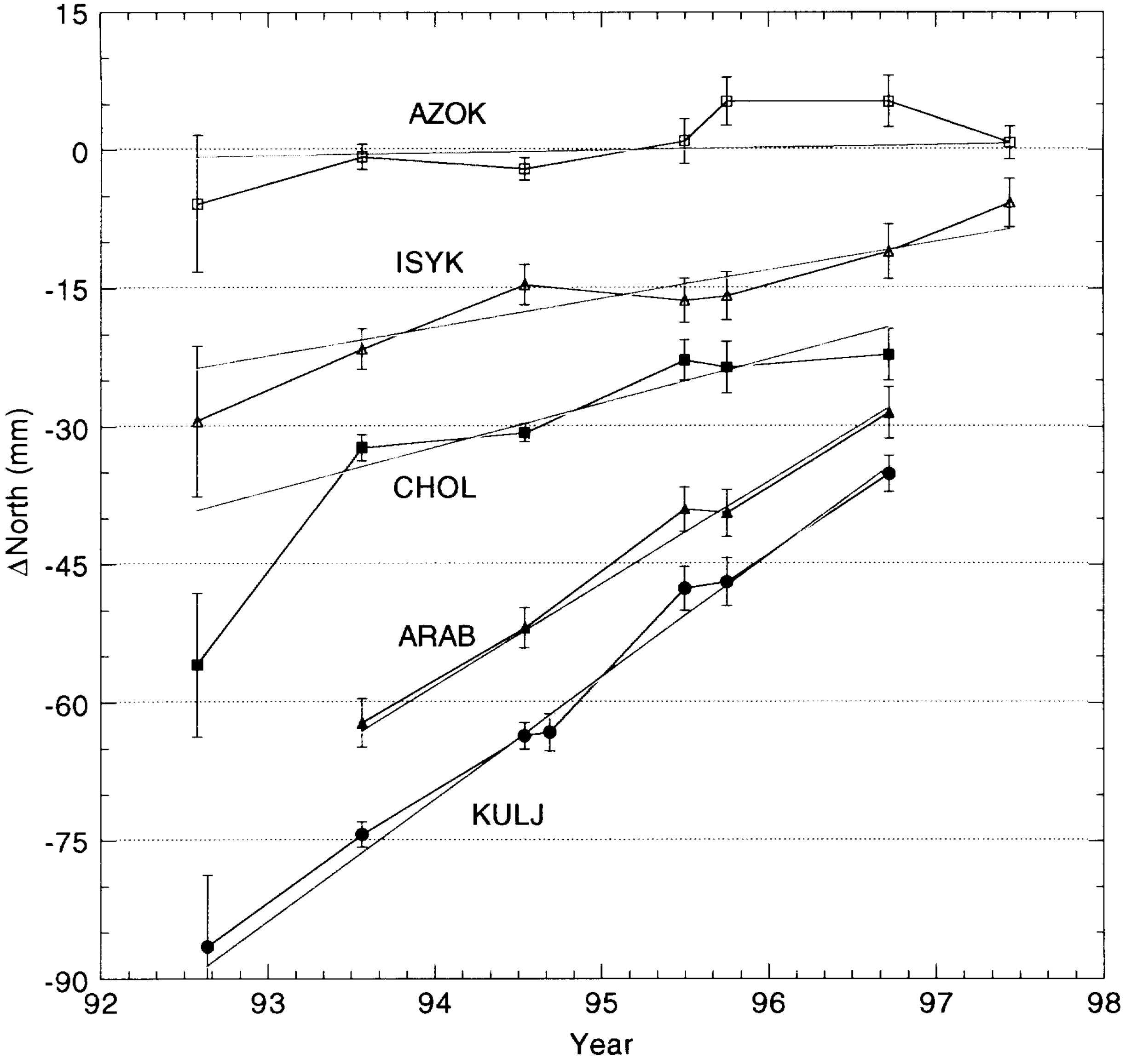
North velocity Longtitude band profiles




AZOK
ISYK
CHOL
ARAB
KULJ
ΔNorth (mm)
Year
15
0
-15
-30
-45
-60
-75
-90
92
93
94
95
96
97
98