LANDSLIDE INVESTIGATIONS IN SOUTHERN KYRGYZSTAN BASED ON A DIGITAL ELEVATION MODEL DERIVED FROM STEREOSCOPIC MOMS-2P DATA

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Working Group IC-24

KEY WORDS: Landslides, GIS, Photogrammetry, MOMS, DEM, GPS, Accuracy, Application

ABSTRACT

In Kyrgyzstan (Central Asia) large landslides are widespread at the eastern rim of the Fergana Basin in an area of active mountain building (Pamir-Tien Shan). Because of the large number of landslides and their difficult accessibility in mountainous terrain the potential of GIS-based analysis of satellite remote sensing data is investigated. This goal requires a spatially and thematically consistent digital database including high resolution digital topographic data as a key element. For this purpose a Digital Elevation Model (DEM) was generated from data of the German multi-line scanner MOMS-2P (Modular Optoelectronic Multispectral Scanner). Processing steps included automated image matching for tie point generation between the 3 stereo strips, photogrammetric block adjustment for reconstructing the exterior and interior orientation of the camera, and finally DEM interpolation. Geodetic GPS measurements were carried out to determine ground control points (GCP) for photogrammetric point determination and independent check points (CP) for assessment of height accuracy of the final DEM. Height accuracy is described by mean and standard deviation of differences between GPS and DEM heights and amounts to 1.1 +/- 17.3m based on 36 CP. In a second step, orthoimages of the 4 MOMS-2P channels were derived. Both MOMS-2P stereo products were analyzed for their suitability investigating landslide phenomena in the Maili-Suu test area. GIS-based analysis including perspective visualizations, surface profiling and derivation of quantitative relief parameters led to topography-based identification of tectonically active elements as one major factor for initiating landslides. The stereo products also allowed detailed analysis of a single landslide. In case of the Kashgarta landslide spatial interference between displaced masses and surrounding stable areas was investigated incorporating geological information. These investigations showed that height accuracy and morphological detail of MOMS-2P stereo products are appropriate for regional satellite remote sensing based analysis of landslide processes in this area.

1 INTRODUCTION

In Kyrgyzstan large landslides are widespread at the eastern rim of the Fergana Basin in the foreland of the Tien Shan (Fig. 1). Single events can cause mass movements of more than one million cubic meters within short periods of time. Every year landslides lead to extensive damage of settlements and infrastructures and to loss of human lives. Spatial assessment of landslide hazard is subject of collaboration between the GeoForschungsZentum (GFZ) Potsdam and the Ministry of Emergency and Civil Defence (MECD) in Kyrgyzstan. The goal is to develop a GIS-based approach incorporating satellite remote sensing data and existing geoscientific information about the present stage of landslide activity and the geological and physical-geographic conditions causing slope failures.

This goal requires a spatially and thematically consistent digital database. A Digital Elevation Model (DEM) is a key element of such a database, since relief is an integrative expression of geomorphic and tectonic processes. Detailed information about topography is also required for topographic correction and thematic analysis of satellite remote sensing data in mountainous terrain. The northern part of the study area was covered by MOMS-2P data take in stereo mode D (Fig. 1) during the operation of the German MOMS-2P sensor on board the Russian MIR station. These MOMS data represent a unique opportunity for generating a DEM for a large part of the study area.

This paper describes the procedure of DEM generation under the specific conditions of the study area and evaluates the result assessing GPS-based height accuracy. In a second step orthoimages of the 4 MOMS channels are derived. The suitability of these stereo products for investigating landslide phenomena is demonstrated for the Kashgarta landslide in the Maili-Suu river basin (Fig. 1). Like the whole region, this test area is part of the active tectonic collision zone between the Eurasian and the Indian Plates. Ongoing tectonic activity results in an active development of the Pamir-Tien Shan orogen causing earthquakes and mass movements (landslides, rock falls). Landslides mainly occur at elevations between 700 and 2000m in weakly consolidated sediments of the topographically rising rim of the Fergana Basin below its transition into the high mountainous terrain.

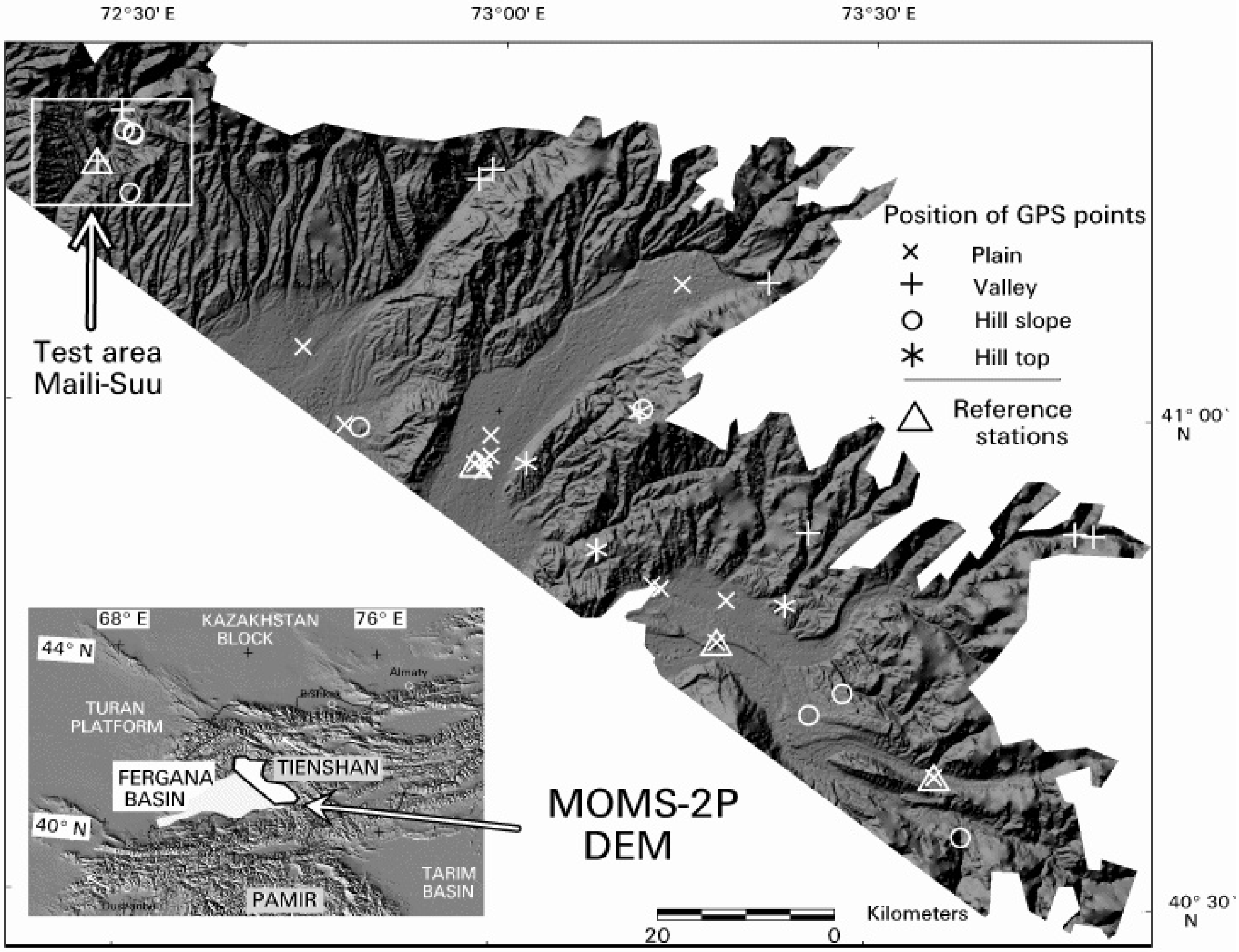

Fig. 1 DEM (50m raster size) derived from stereoscopic MOMS-2P data overlaid by GPS check points

2 INPUT DATA FOR DEM GENERATION

Remote sensing based DEM generation requires stereo image data, precise 3-D coordinate information of ground control points (GCP) and independent check points (CP). MOMS-2P data were acquired in stereo mode D on the 29th of June 1998. Topographic ground control information were obtained by geodetic GPS observations in July 1999. In the following two sections both input data sources are described in more detail.

2.1 MOMS-2P data

MOMS (Modular Optoelectronic Multispectral Scanner) is a German spaceborne pushbroom scanner for high resolution (HR), multispectral (MS) and threefold along-track stereoscopic imaging (Kaufmann et al., 1989; Seige et al, 1999). The stereo-module consists of a HR nadir looking lens with a focal length of 660mm and two inclined lenses with 237mm focal length. Thus, the Earth´s surface is imaged three times from three different directions within approximately 40 seconds only, corresponding to an orbital distance of approximately 300km. This along-track stereo principle is highly advantageous for image correlation in the data evaluation process, since all three image strips are recorded under more or less the same imaging conditions. The stereo angle of 21.4° results in a base/height ratio of approximately 0.8. The multispectral-module consists of two additional lenses with 220mm focal length comprising 2 CCD arrays for narrow-band image acquisition in the blue, green, read and near infrared wavelength ranges.

Three scenes (60, 61, 62) MOMS-2P data take T0906 include the northernmost part of the Fergana Basin (elevation below 700m N.N.) and its rim between 700 and 2000m where the majority of landslides occur. Since cloudiness is mainly limited to higher areas, a large part of the terrain affected by landslides is visible in the MOMS-2P scenes. MOMS-2P data acquisition took place from an altitude of 372 km. Each scene covers an area of 100 by 100km. Stereo imaging mode D combines two inclined panchromatic stereo channels (6, 7) and two nadir looking spectral channels in the blue (1) and near infrared (4), whose spatial resolution is 17m.

2.2 GPS measurements

Precise 3-D coordinates of ground control points (GCP) and independent check points (CP) were obtained by geodetic GPS measurements within an area of 150km length and 60km width (Fig. 1) using LEICA (SR9500) receivers. Network planning aimed for a GPS accuracy of one meter in X, Y, Z and a mean distance between locations of 25 - 30km. GPS observations took place simultaneously for a fixed reference station and mobile rover points. Because of the size of the study area four reference stations had to be established (Fig. 1). Based on experiences from previous campaigns (Roessner, 1997), observation time was 30 minutes for trigonometric points and 15 minutes for other field points.

Possible locations for GCP were preliminarily selected based on MOMS-2P stereo channel 7 and topographic maps. For their identification in the field, black-and-white hardcopies (approx. scale of 1:25.000) were used which allowed single pixel identification. During the GPS campaign 59 object points were observed (total of 83 points). Correspondence between image points in the MOMS-2P data and object points in the field could be achieved with an accuracy of about one pixel. In some cases, steep relief and absence of man-made structures led to uncertainties in determining overall point positions. Such points become evident and can be eliminated in stereo data processing (3.2).

Precise geographic WGS-84 coordinates were obtained during post-processing of the GPS observations with the software GPSURVEY (TRIMBLE GPS). Reference station coordinates were determined independently at the GFZ Potsdam with the EPOS software (Angermann et al., 1997) achieving an absolute accuracy of a few centimeters in X, Y, Z. These coordinates and precise ephemeris were introduced into GPSURVEY baseline processing. In the result average internal accuracy for all rover points amounts to 0.08m in X, 0.07m in Y and 0.04m in Z leading to an average point error of 0.11m. Assuming a factor of 10 between internal and external GPS accuracy, the results are in the expected range of accuracy and represent high-quality control points.

3 STEREO DATA PROCESSING

In the past it was demonstrated that stereo processing of MOMS-2P 3-line imagery allows for DEM generation with 10m accuracy and better (Kornus et al., 1999). The main steps of the developed approach and results of its customization for the study area in Kyrgyzstan are described in the following sections.

3.1 Image matching for tie point generation

DLR software for automatic image matching - developed for the stereo scanner projects MEOSS, MOMS-02, and MOMS-2P - was used to generate tie points between the image strips of the 3 looking directions. Though massive numbers of tie points are generated by this software (in our case about 424,000 points), the emphasis was put on the quality of the input points for the bundle adjustment. The actual matching schemes are described by Lehner and Gill, (1992) and Lehner and Kornus, (1995). Subpixel accuracy was achieved by local least squares matching (LLSQM). For input to the photogrammetric adjustment a coarse grid of best points (here 3557 points) was selected. Criteria for this selection are the final correlation coefficient after convergence of the LLSQM (threshold used is 0.8) and the stability of the results while interchanging the template role of the images in the stereo pairs (threshold here is 0.1 pixel).The thinning is done so to get a fairly homogeneous distribution for the whole strip.

3.2 Bundle adjustment

The functional model of the photogrammetric bundle adjustment used here is based on the principle of orientation images (OI), as originally proposed by Hofmann et al., (1982). The extended functional approach used for MOMS image orientation is comprehensively described in Kornus, (1999). Recent investigations still showed some problems introduced by high frequency attitude variations during MOMS-2P data recording, which could be partly modeled by means of a dense GCP distribution (25km - 30km mean distance) (Kornus et al., 1999). The real variations have apparently been filtered out in the provided gyro data files. With correctly reprocessed gyro data height, accuracies of 7m and better are expected. In the bundle adjustment four groups of input information are entered. These are image coordinates of tie points, camera calibration parameters, ground control information and navigation data which are explained in more detail in the following:

1. From image matching (3.1) a subset of 3557 regularly distributed tie points were selected and introduced with an a priori standard deviation of 0.2 pixel.
2. The camera calibration parameters were derived from MOMS-2P geometric laboratory calibration, conducted at DaimlerChrysler Aerospace Company (Dasa, former MBB), the manufacturer of MOMS-2P. Earlier investigations showed, that significant deviations from the lab-calibrated parameters and also temporal variations have occurred (Kornus et al., 2000). Therefore, the camera parameters were introduced as observations with low weights into the adjustment to allow for self-calibration.
3. From the 59 GPS points, 11 points had to be eliminated due to gross errors, recognized by corrections 3 times bigger than the root-mean-square (rms) value derived from all points. This is a result of the above mentioned problems in identification of some point positions in the field (2.2). From the remaining 48 GCP 41 were introduced with an a priori standard deviation of 10m in planimetry and 5m in height. The rms-error of the final corrections was 7.9m, 14.3m and 1.6m in X, Y, and Z.
4. From the MOMSNAV navigation dataset only the orbit data were exploited while the attitude data were neglected due to the problems mentioned above. At the German Space Operations Center (GSOC) of the DLR the orbit positions are derived by post-processing of the onboard processed GPS data, which are downlinked from the MIR station. These relatively inaccurate positions are interpolated with high precision orbit models. The resulting orbit has an internal accuracy of 1-3m and an absolute accuracy of 30-50m (Gill, 1997).

For the evaluated strip, consisting of 28728 image lines, 19 OI were employed. The distance between the OI was set to 1512 image lines, corresponding to 3.7 seconds flight time. Both GCP and orbit positions were previously transformed into a local cartesian topocentric coordinate system (LTS) based on the WGS-84 ellipsoid, with its origin close to the center of the evaluated area. As result the estimated parameters of interior and exterior orientation were obtained, serving as input for the steps described in 3.4 and 3.6.

3.3 Image matching for dense parallax measurements

The Otto-Chau region growing concept in the implementation of Technical University Munich (Heipke and Kornus, 1991) was used to generate a very dense grid in two separate runs of parallax measurements trying to match every pixel and every fourth pixel. As described earlier, basic matching algorithm is LLSQM. 3 image pairs were used to check for blunders at this stage. The whole process consists of the following four steps:

1. computing mass points for backward/forward image pair (bf)
2. evaluating backward/nadir and forward/nadir matching runs starting from the coordinates given by the bf-results
3. using the mean of the two resulting nadir coordinate pairs
4. discard the match if the distance of the mean to the original coordinates exceeds a threshold (here put to 0.5 pixel)

3.4 Transformation of mass points into object space

Next, the dense parallax measurements were transformed into the LTS coordinate system by forward intersection using the estimated orientation of the bundle adjustment. Only points imaged by all three looking directions were used. Here, the object point coordinates are derived from 6 image coordinates by adjustment. If the correction to an image coordinate exceeds a threshold (here put to 0.5 pixel), the point is discarded. After transforming the LTS into geographic WGS-84 coordinates, X, Y coordinates were transformed into the state coordinate system of Kyrgyzstan (Transverse Mercator Projection related to the Krasovsky Ellipsoid, Datum Pulkovo 1942) using the ARC/INFO software with user-defined datum definition. The ellipsoid heights were converted to orthometric heights using the world-wide 15 minute gridded geoid heights provided by the National Imagery and Mapping Agency (NIMA, 1999).

3.5 Generation of a regular raster DEM

For interpolation of the regular raster DEM from the transformed mass points the software package LISA (Linder, 1999) was used. Parameterization of the interpolation procedure defines the accuracy of preservation of topographic elements originally contained in the mass points. The goal was to optimize between morphological detail and suppression of noise. For the 18km by 12km test area of Maili Suu (Fig. 1) different versions of a regular raster DEM were derived using a sliding plane as interpolation function. Based on the mass point dataset with 4 pixel minimum point distance (70m), various DEM with grid point spacing of 50, 75, 100m and median filter sizes of 3x3, 5x5, 7x7 were investigated. For comparison interpolation accuracy of DEM raster generation was determined in calculating elevation differences between the original height of mass points and their representation in the regular raster DEM and in analyzing their frequency distributions and statistical parameters. Best representation of original mass points was achieved for a DEM interpolation of 50m raster size with subsequent 3x3 filtering. This parameterization was applied to the whole study area (Fig. 1). For the Maili Suu test area a DEM with 25 m raster size and 3x3 filtering was generated from the dataset with 1 pixel minimum point distance (17 m). Comparisons of both DEM were based on interpolation accuracy and slope frequency distributions. The 25m-DEM shows a slightly better representation of original mass point elevations. Slopes derived from the 50-m DEM are lower in comparison to the 25m-DEM indicating a greater morphological detail contained in the latter one.

3.6 Derivation of orthoimages using DEM and estimated interior and exterior orientations

After the estimation of the interior and exterior orientations by bundle adjustment and the derivation of the DEM, the imaging geometry is fully known (to the indicated accuracy). Thus, orthoimages of all 4 MOMS channels can be generated. This has been done for the Maili Suu test area based on the 25-m DEM. The result is a multispectral orthoimage fitting to the DEM. In case of MOMS stereo mode D this is a big improvement, since nadir looking channels 1 and 4 and stereo channels 6/7 are now available as geometrically identical channels. This way channel combinations 1-6-4 / 1-7-4 cover almost the whole range of the VIS/NIR part of the spectrum between 440 and 810nm and allow true RGB visualizations leading to a much better spectral discrimination between different objects.

4 ASSESSMENT OF ABSOLUTE HEIGHT ACCURACY BASED ON GPS CHECKPOINTS

Absolute height accuracy of the 3x3 filtered and 50m raster size DEM was determined within a 150 by 60km part of the DEM where GPS observations of independent check points (CP) were obtained during the 1999 and a previous 1998 GPS campaign (Fig. 1). Spatial consistency between both campaigns was checked based on 3 locations with double observations. The average difference between the independently determined coordinates amounts to 0.06m in X, 0.1m in Y and 0.04 m in Z. From all possible CP only those were selected which were situated in areas with mass point coverage. In the result, for a total of 36 CP elevation differences (d) between GPS heights and heights interpolated from the raster DEM at the same X, Y positions were calculated. For an empirical estimate of height accuracy mean (d_{mean}) and standard deviation (d_{stdev}) were determined based on these elevation differences (Tab. 1). For all 36 points, height accuracy amounts to 1.1m +/- 17.3m. This result is in the expected range of accuracy taking into account problems in image-based identification of GCP (2.2) and the highly dissected relief of the study area leading to a stronger influence of positional accuracy (X, Y) on height accuracy (Z). Tab. 1 shows a statistical analysis of the CP in dependence on their relief position (Fig. 1). Best height accuracy is obtained for points situated in plains approaching accuracy of 10m which had been achieved in previous studies (Kornus, 1999). Largest standard deviations occur for points along hill slopes and valleys. The latter ones show a tendency of being filled in contrast to hill tops being lowered. The limited number of CP reduces the statistical significance of the results. However, the obtained height accuracy satisfies the needs of landslide analysis since it is of subordinate importance in comparison to morphological correctness of the DEM which will be discussed in the following section (5).

control points	**number of points**	**d_{min} in m**	**d_{max} in m**	**d_{mean} in m**	**d_{stdev} in m**
all	36	-38.7	29.3	1.1	17.3
plain	15	-11.6	19.2	3.3	7.7
valley	8	-27.2	18.5	-2.2	15.5
hill slope	9	-38.7	29.3	7.0	27.3
hill top	4	11.5	22.5	18.3	4.7

Tab. 1 Height accuracy in GPS points (CP) for 50m-DEM (3x3 filtered) in dependence on relief

5 DEM-BASED CHARACTERIZATION OF KASHGARTA LANDSLIDE

The Kashgarta landslide in the Maili Suu test area (Fig. 2) is the biggest mass movement in the Upper Maili Suu river basin. The landslide developed in spring 1994 and has displaced a total mass of about 10 million tons until the end of June 1998. The Maili Suu area characterized by high landslide intensity is situated in the transitional zone between the Variscan consolidated basement block in the north (Arslanbob block as part of the Southern Tien Shan) and the Fergana Basin in the south. In the area of the Kashgarta landslide the northern rim of the Fergana Basin is formed by an anticline consisting of weakly consolidated sediments (Upper Cretaceous up to Paleogene) which is folded along an E-W axis. In this tectonically active area landslides are caused by complex interactions between endogenic and exogenic factors including tectonic structures, lithology, relief and climate.

Since the Kashgarta landslide is only one prominent example of a large number of landslides occurring in a 50km wide belt along the eastern rim of the Fergana Basin, the goal is to develop effective satellite remote sensing based methods for an inventory of present landslide activity (last 10 years) and for a regionalisation of landslide-causing factors. The main emphasis is put on determination of relevant geological, tectonic and geomorphological indicators for landslide activity using GIS-based visual and quantitative analysis. For this purpose a spatial database consisting of topographic maps (1:100.000), MOMS-2P based DEM, MOMS-2P orthoimages, geometrically fitting Landsat-TM and SAR (ERS-1/2) data, geological information and field investigations has been established (Roessner et al., 1999). In the following, results of GIS-based analysis are discussed for the Kashgarta landslide.

In the Upper Maili Suu river basin the dominance of geological structures initiating landslide processes requires detailed 3-D analysis of structural elements developed by the interaction between tectonic (endogenic) and mass wasting (exogenic) processes. For this area the derived MOMS-2P 25m-DEM and orthoimage are the first digital topographic database of sufficient spatial resolution allowing detailed GIS-based analysis by perspective visualizations, surface profiling, derivation of quantitative parameters (e.g., slope) and their analytical combination (Fig. 2). For structural investigations perspective DEM visualizations were overlaid by RGB-orthoimages and geological map information. They allowed identification of structural and tectonic features, such as fracture or shear elements and faults forming the basis for genetic interpretation of structural elements influencing slope failure (Wetzel et al., 2000). In the area of the Kashgarta landslide shear zones could be identified which cut the older N-E anticline. Within these shear zones young extension has developed showing a close spatial relationship to the landslides. Based on these observations it is assumed that the landslide was tectonically initiated leading to a primary displacement of the weakly consolidated Upper Cretaceous sediments (area above Profile A in Fig. 2). A more detailed analysis of landslide related tectonic structures can be found in Wetzel et al. (2000). The results represent one of the inputs for future GIS-based factor analysis of landslide hazard.

Besides regional analysis of larger structures, high resolution MOMS-2P stereo products also allow detailed analysis of a single landslide which is demonstrated in Fig. 2 showing a perspective visualization of the DEM overlaid by the orthoimage and the courses of the profiles A, B, C. The profiles are the result of a combined GIS analysis including DEM, orthoimage and geological map information. Profiling the DEM overlaid by the orthoimage allowed precise differentiation between displaced masses (high albedo due to missing vegetation) and stable (vegetated) parts of the profile. This change is also reflected in the topographic profile in the form of small morphological steps (profile A). Slope discontinuities within displaced masses indicate secondary movements. Integration of geological information led to the final cross-sections of Fig. 2. In the middle part of the valley (Profile A) Mid-Quaternary (Q_2) loesses were partially displaced by the landslide. In contrast, slopes within Tertiary units (P_{G3} and $N_{1/2}$) situated further downstream are stable and only the bottom of the valley is filled by displaced masses (Profile B). Profile C shows a cross-section which has not yet been affected by accumulation. Additional characteristics of the landslide could be obtained from slope classification. Areas of landslide deposition are dominated by slopes between 0 and 9 degrees reaching maximum values between 10 and 14 degrees in the area above Profile A. The main scarp of the landslide can clearly be identified at its upper rim by high slope values between 20 and 34 degrees. Stable flanks (Profiles B, C) are characterized by slopes greater than 15 degrees.

6 CONCLUSIONS

GIS-based satellite remote sensing in mountainous terrain requires digital topographic information (DEM) of a spatial resolution comparable to the satellite data. In Kyrgyzstan stereo satellite data are the only possible source for effective generation of such a DEM for a larger area. Stereo data obtained by MOMS represent an ideal opportunity due to threefold along-track stereoscopic imaging technology. The previously developed approach for stereo processing of MOMS-2P 3-line imagery was successfully applied to three scenes (60-62) of MOMS-2P data take T0906 covering the transitional zone between Fergana Basin and Tien Shan which is intensely affected by landslides. In the result a state coordinate based DEM of 50m raster size could be generated for 150 by 60km large area. The achieved absolute height accuracy of 1.1 +/- 17.3m represents a good quality DEM taking into account the limited number of control points which could be determined in the field by geodetic GPS measurements. In this process highest uncertainty was introduced during identification of corresponding locations for GCP in the image data and in the field which is caused by the combination of a complicated field situation (lack of larger man-made structures) and the limited spatial resolution of the MOMS-2P data.

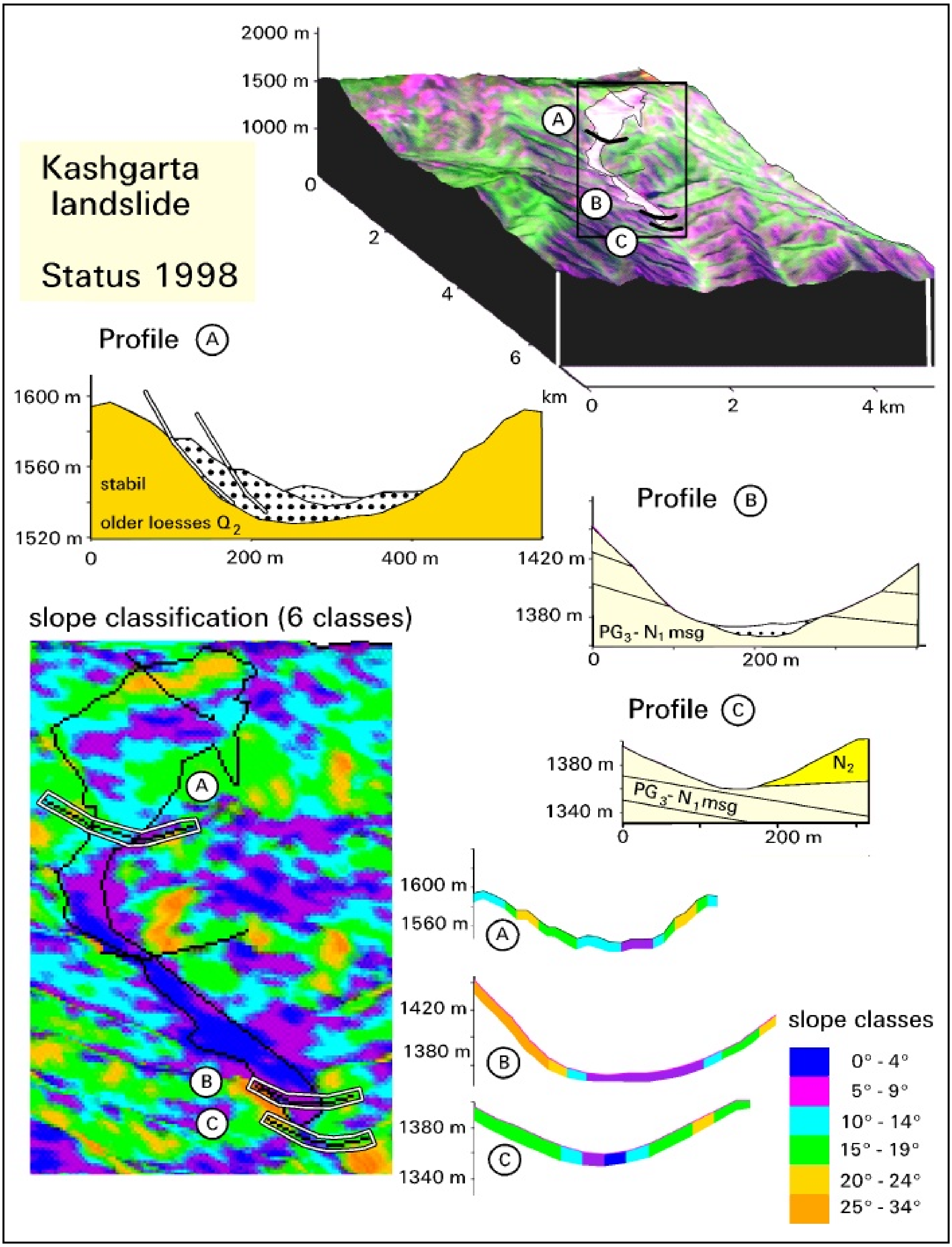

Fig. 2 GIS-based analysis of Kashgarta landslide using MOMS-2P stereo products and geological information

Stereo image matching for the Maili-Suu test area was performed for each pixel allowing the interpolation of a DEM with a 25m raster size forming the basis for orthoimage generation. A GIS-based analysis of these stereo products in combination with geological information show their great potential for investigating structural settings as a major factor in landslide initiation. In this connection, derivation of quantitative relief parameters, perspective visualizations and complex profiling incorporating different data sources are powerful tools for analyzing landslides in their larger spatial context. A detailed analysis of the Kashgarta landslide showed that the great morphological detail contained in the MOMS-2P stereo products allows investigation of interference between displaced masses and the stable surroundings of the landslide. Future work will focus on a systematic inventory of different landslide types and landscape parameters relevant for landslide processes which can be derived quantitatively from stereo products and additional satellite remote sensing data.

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