Monitoring, Geomorphological Evolution and Slope Stability of Inca Citadel of Machu Picchu: Results from Italian INTERFRASI project

14

P. Canuti, Claudio Margottini, N. Casagli, G. Delmonaco, L. Falconi, R. Fanti, A. Ferretti, G. Lollino, C. Puglisi, D. Spizzichino and D. Tarchi

Abstract The Geology of Machu Picchu area is characterised by granitoid bodies that had been emplaced in the axial zones of the main rift system. Deformation of the granite, caused by cooling and tectonic phases, originated 4 main joint sets, regularly spaced (few decimetres to metres). Several slope instability phenomena have been identified and classified according to mechanism, material involved and state of activity. They are mainly related to rock falls, debris flows, rock slides and debris slides. Origin of phenomena is kinematically controlled by the structural setting and relationship with slope face (rock falls, rock slide and debris slides); the accumulated materials is the source for debris flow. Geomorphological evidences of deeper deformations are currently under investigation.

A low environmental impact monitoring system has been established on the area having the purpose to minimize equipments usage and, in the mean time, to collect reilable data on surface deformations. The monitoring network comprise

P. Canuti (✉)
University of Firenze, Department of Earth Sciences, Via Giorgio La Pira 4, 50121, Firenze, Italy

C. Margottini
ENEA, Via Anguillarese, 301 – 00060 S. Maria di Galeria (Rome) Italy; ISPRA – Italian Institute for Environment Protection and Research – Via Curtatone 3, 00185, Rome, Italy

N. Casagli
University of Firenze, Department of Earth Sciences, Via Giorgio La Pira 4, 50121, Firenze, Italy

G. Delmonaco
ENEA, Via Anguillarese, 301 – 00060 S. Maria di Galeria (Rome) Italy; ISPRA – Italian Institute for Environment Protection and Research – Via Curtatone 3, 00185, Rome, Italy

L. Falconi
ENEA, Via Anguillarese, 301 – 00060 S. Maria di Galeria (Rome) Italy; Consorzio Civita, Via del Corso 300, 00186, Rome, Italy

R. Fanti
University of Firenze, Department of Earth Sciences, Via Giorgio La Pira 4, 50121, Firenze, Italy

A. Ferretti
Tele-Rilevamento Europa, T.R.E., Via Vittoria Colonna 7, 20149, Milano, Italy

G. Lollino
CNR-IRPI Torino, Strada delle Cacce 73, 10135, Torino, Italy

C. Puglisi
ENEA, 301 – 00060, Via Anguillarese, S. Maria di Galeria, Rome, Italy

D. Spizzichino
Consorzio Civita, Via del Corso 300, 00186 Rome (Italy); ISPRA – Italian Institute for Environment Protection and Research – Via Curtatone 3, 00185, Rome, Italy

D. Tarchi
European Commission, Joint Research Centre, SERAC Unit, Via E. Fermi, 1 – TP 723, 21020, Ispra (VA) Italy

K. Sassa, P. Canuti (eds.), *Landslides – Disaster Risk Reduction*,

a GPS, multitemporal laser scanner survey, Ground based Radar interferometry (GB-SAR) and Satellite Interferometric Synthetic Aperture Radar (InSAR).

The preliminary results are partially confirming the field evidences of slope deformation but, in the mean time, they require a longer period of observations since the sliding processes are relatively slow.

Keywords Geomorphology • Slope instability • GPS • Radar • Monitoring • Machu Picchu

14.1 Geological Setting

The high Eastern Cordillera of Peru formed as a result of inversion of a Late Permian-Triassic rift system (e.g. Semper et al., 2002). The Geology of Machu Picchu area reflect the same pattern.

The area (Fig. 14.1) is characterised by granitoid bodies that had been emplaced in the axial zones of the main rift system that are now exposed at the highest altitudes, together with country rocks (Precambrian and Lower Paleozoic metamorphics) originally constituting the rift 'roots'. The Machu Picchu batholith is one of these Permo-Triassic granitoid bodies (a biotite Rb-Sr age of 246 ± 10 My by Priem et al. is reported for this intrusion in Lancelot et al., 1978).

The bedrock of the Inca citadel of Machu Picchu is mainly composed by granite and subordinately granodiorite. This is mainly located in the lower part of the slopes (magmatic layering at the top). Locally, dikes of serpentine and peridotite are outcropping in two main levels; the former is located along the Inca trail, near Cerro Machu Picchu (vertically dipping), the latter is located along the path toward "Templo de la Luna" in Huayna Picchu relief.

Superficially, the granite is jointed in blocks with variable dimensions, promoted by local structural setting. The dimension of single blocks is variable from 10^{-1} to about $3*10\ m^3$.

Soil cover, widely outcropping in the area, is mainly composed by individual blocks and subordinately by coarse materials originated by chemical and physical weathering of minerals.

Part of the slopes exhibit debris accumulation as result of landslide activity. Grain size distribution of landslide accumulation are closely related to movement types and evolution.

Talus and talus cones are composed by fine and coarse sediments, depending from local relief energy.

Alluvial deposits outcrop along the Urubamba river and its tributaries. They are composed by etherometric and polygenic sediments, that may be in lateral contact with the talus deposits.

Anthropic fill and *andenes*, on top of Citadel, reflect the work of Inca civilization in the area (Fig. 14.2).

Fig. 14.1 General view of Machu Picchu area

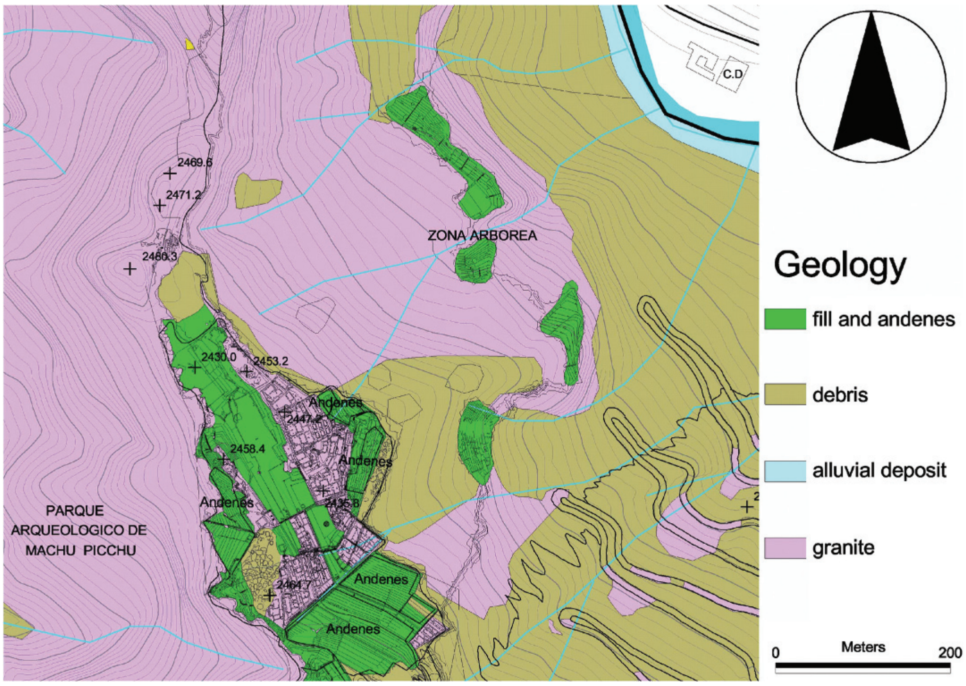

Fig. 14.2 Geological map of the Inca Citadel of Machu Picchu

Mechanical proprieties of local material are reported in the following Table 14.1.

14.2 Structural Setting

Deformation of the granite is highly localised into differently oriented sets of regularly spaced (few decimetres to metres) shear zones (Mazzoli et al., 2005). All of these shear zones show well-defined, sharp, fault-like discontinuities, characterised by slickenside surfaces and shear fibres. These indicate consistent reverse to oblique-slip (transpressional), to strike-slip kinematics, depending on fault set attitude. Most of these shear planes show limited measurable displacements (a few centimetres to decimetres being common) and essentially undeformed wall rock. However, in several instances ductile deformation of the granite has also occurred along the walls of fault-like discontinuities. These deformation zones range from a few centimetres- to decimetres-thick mylonite horizons, showing sharp contacts with surrounding undeformed granite, to more continuous shear zones displaying sigmoidally-shaped S foliations (progressively decreasing in intensity in wall rock granite) and S-C or composite S-C-shear band fabrics. Mylonite microstructures are characterised by extensive dynamic recrystallisation of quartz and grain-size reduction. Chlorite and white mica-dominated mineral assemblages point to lower greenschist-facies conditions for the deformation. Inversion of fault-slip data indicates that the latter occurred as a result

Table 14.1 Geotechnical parameters and proprieties

	Density (KN/m^3)	Ed (MPa)	Kn (MPa)	v	Sigmaf (MPa)	Tensile strength (MPa)	II(°)	c (kPa)
Granite	23–25	80,000–90,000	20–100	0.15	50–250	7–13	33.5–40.5	220–355
Granodiorite	23–25	100,000–150,000	20–100	0.15	60–250	7–13	35–42	270–355
Superficial cover	25	–	–	–	–	–	32	270
Talus	18–25	–	–	–	–	–	34–38	0

of mean N60°E oriented shortening, well compatible with regional data from the nearby Cusco area (Carlotto, 1998). Structural analysis clearly suggests that the analysed shear zones form part of a larger population of regularly spaced surfaces that most probably originated as early (cooling) joints in the igneous rock. Reactivation of differently oriented sets of precursor joints allowed the granite to deform effectively by relatively small displacements occurring on a very large number of shear zones, the strain being therefore localized at the m-scale, but distributed at the km-scale.

The structural settings of terrains is finally related to the main following dip orientations/dipping:

a) 30°/30° in the Machu Picchu hill ;
b) 30°/60°;
c) 225°/65;
d) 130°/90°.

Secondary systems (e.g. 130°/45°, 315°/30° and 310°45°) have been also surveyed in the area, with minor relevance.

14.3 Geomorphology and Slope Instability

During three joint missions in Machu Picchu in 2003 and 2004, the group performed a geomechanical and geomorphological survey of the entire area. Field observations were integrated with interpretation of stereoscopic aerial photos and of two optical very-high-resolution satellite images (*Quickbird*) dated 18 June 2002 and 18 May 2004, respectively.

The general morphological features of the area are mainly determined by the regional tectonic uplift and structural setting. As consequence, kinematic conditions for landslide type and evolution are closely depending on the above factors.

Several slope instability phenomena have been identified and classified according to mechanism, material involved and state of activity (Fig. 14.3). They are mainly related to the following: rock falls, debris flows, rock slides and debris slides. The area of the citadel has been interpreted as affected by a deep mass movement (Sassa et al., 2001, 2002) that, if confirmed by the present day monitoring systems, it could be referred to a deep-seated gravitational slope deformation (DSGSD), probably of the type of the compound bi-planar sagging (CB) described by Hutchinson (1988). A main trench with NW-SE trend, related to a graben-like structure, is located within the archaeological area and supports this hypothesis. Other trenches are elongated in the dip direction of the slope.

In the SW cliff the local morphological depends on the intersection between the systems 225°/65° and 130°/90° which bounds lateral evolution. This kinematic condition causes high angle rock slide which very often evolve in rock falls. These are also conditioned by 30°/30° and 30°/60° systems which originate overhanging blocks. The SW slope exhibit some morphological terraces, regularly spaced, the origin of which it is still under investigation (fluvial erosion, sagging, joint, etc).

The morphological evolution, in NE flank below the Inca Citadel, is constrained prevalently by the 30°/30° and 30°/60° systems and marginally the 225°/65° one; the intersection of the first two systems with slope face it is kinematically compatible with the occurrence of planar rock slides; the intersection of slope face with the 225°/65° is kinematically compatible with rock falls. Rock slides and rock falls may produce blocks with dimension variable from 10^{-1} to 10^2 m^3.

Debris produced by rock slides and rock falls, as well as from weathering processes is periodically mobilised as debris slides and debris flow. The most recent phenomenon occurred in 1995 along the "carrettera" Bingham. Debris slides and debris flows are characterised by an indifferentiated structure varying from chaotic blocks immersed on coarse sand matrix. The grain size distribution is mainly depending on the distance from the source areas and slope angle.

Finally, it is interesting to notice, on the NE side, the presence of a large debris accumulation, just below the citadel, presently being eroded by all around dormant slides. The accumulation it is probably the result of an old geomorphological phenomena now stabilised, still not clear in its original feature. Anyway, the mass movements occurred certainly before the Inca settlement since some of their terraces (andenes), are founded over this accumulation area.

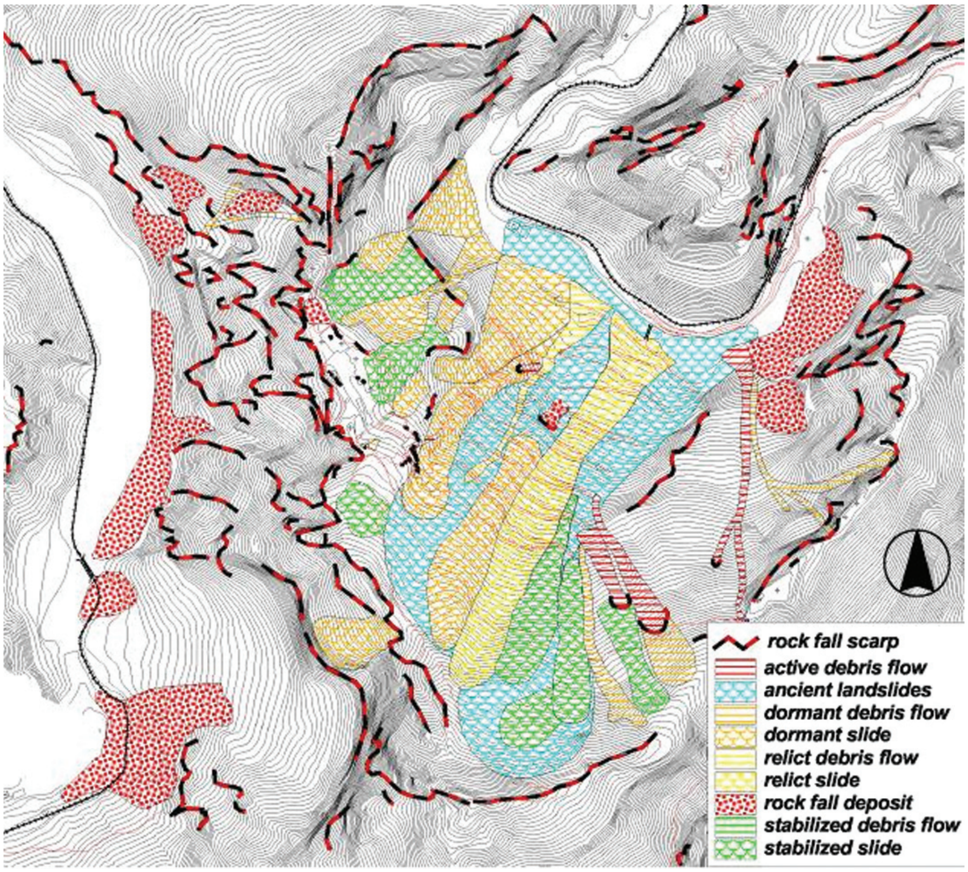

Fig. 14.3 Geomorphological map of the area

14.4 GPS Monitoring Network

A GPS network was installed in September 2003, in the Urubamba valley and Machu Picchu citadel. The GPS network is constituted by 3 control points (*a priori* FIXED) and 11 rover points installed inside the citadel's area.

A first survey was conducted in September 2004, after one year of monitoring. Displacement of rover points of the citadel was calculated using baselines generated from the adjusted geodetic coordinates of reference points. The results show that the points where a displacement was appreciated are (Table 14.2):

Table 14.2 Displacement detected along the three axis (N, E, h) for points 9 and 10. Red data are considered reliable (for location see Fig. 14.7)

	Delta N [m]	Delta E [m]	Delta h [m]
9	0.012	−0.002	0.002
10	0.010	−0.003	0.009

These results demonstrate how the major displacement vector runs along the North axis; while no significant displacement was detected along the Est and the ellipsoidical height direction.

14.5 Monitoring with JRC GB-SAR

On the 3rd October 2004 the LISA Radar system was installed in a small open area which is part of the old train station in Puente Ruinas, just at the beginning of the road going up to the archeological village (Fig. 14.4). From this site (Fig. 14.5) it is possible to see some buildings of the lower part of the "Ciudadela" entrance and to see the whole

Fig. 14.4 The LISA system

vegetated zone below, where it is expected to observe the possible sliding movement. With the data, that has been continuously acquired up until now, no significant displacements have been detected. Considering the very low displacement rate measured by other monitoring systems, we expect that at least a full year of measurement is needed to get reliable data in order to see every possible small displacement affecting the Inca site.

14.6 Interferometric Synthetic Aperture Radar (InSAR)

Recent advances in optical and radar imagery capabilities, e.g. high spatial resolution, stereoscopic acquisition and high temporal frequency acquisition, the development of new robust techniques based on the interferometric analysis of radar images, such as the Permanent Scatterers Technique (Ferretti et al., 2001), and the possibility of integrating these data within a Geographical Information

System (GIS) have dramatically increased the potential of remote sensing for landslide investigations (Hilley et al., 2004). The resolution is of the order of millimetre.

Due to the very rough topography, steep slopes and local weather conditions the Machu Pichu area is a very challenging test site for the application of satellite radar data. Apart from that, the lack of an historical data-set of ESA-ERS acquisitions prevented – at least in the first part of the

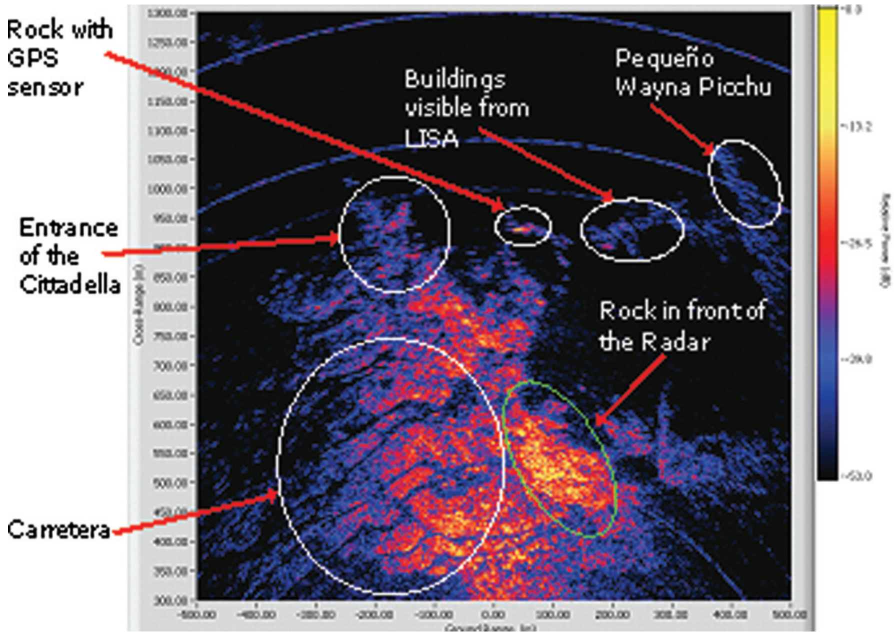

Fig. 14.5 Power image with reference points

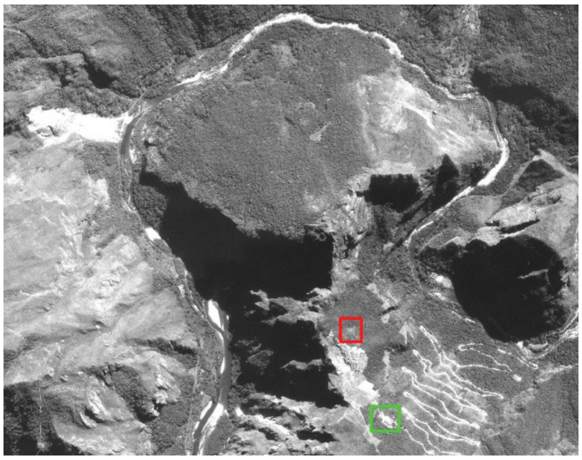

Fig. 14.6 Identification of the two reported PS: the *green* is considered stable and the detected movement is assigned to the *red* PS

project – the application of the POLIMI PS Technique. In fact, the identification of the measurement points and the estimation (and removal) of the atmospheric components can be usually carried out whenever at least 15–20 scenes are available. Unfortunately, just a few ERS scenes were acquired since 1991 for interferometric processing.

Nevertheless, in the framework of the INTERFRASI Project, all satellite radar data acquired by the ESA sensors ERS-1, ERS-2 and Envisat over the area of interest have been processed trying to identify coherent areas where displacement information could be recovered, by applying the conventional approach (DInSAR). However, the coherence level of the interferometric pairs turned out to be to low and no information could be recovered over the AOI.

Due to the lack of ESA-ERS scenes, more than 30 scenes gathered by the Canadian radar sensor RADARSAT in different acquisition modes have been planned and processed. The use of RADARSAT "Fine-Beam" data, characterized by higher spatial resolution with respect to ESA data, turned out to be very important in order to identify good radar targets. Moreover, the shorter repeat-cycle of RADARSAT (24-day rather than 35) allowed the creation of a time series of 16 radar data in two different acquisition modes in about 1 year. The increased resolution allowed the selection of a dozen of "PS Candidates" within the AOI, characterized by a sufficient level of signal-to-clutter ratio (SCR). An in depth analysis of the time series of RADARSAT data, however, highlighted severe decorrelation phenomena probably due to microclimatic conditions at the time of the acquisitions and strong phase artifacts due to tropospheric inhomogeneities. Preliminary results have shown evidence of differential motion between the radar targets of about 5 cm (Fig. 14.6), but the estimation, so far, it has to be considered not totally reliable using the data-set available. An independent confirmation with more PS is required.

14.7 Conclusion

The geological and geomorphological investigations conducted in the area of Machu Picchu highlight the presence on many slope instabilities, mainly with low depth. Several slope instability phenomena have been identified and classified according to mechanism, material involved and state of activity. They are mainly related to rock falls, debris flows, rock slides and debris slides. Origin of phenomena is kinematically controlled by structural asset and relationship with slope face (rock falls, rock slide and debris slides); the so accumulated materials is the source for debris flow.

In the area of the Carretera a precise mapping of debris deposits and past debris flows was carried out, leading to a zonation of processes within the limits of the ancient landslide detected by Sassa et al. (2001). The situation of the slope with the citadel is more complex due to the strong structural control of the master joints on the slope evolution. In this, planar rock slides are mainly affecting the NE flank while rock falls are predominant on SE cliff.

The analysis of monitoring data, integrated with field observations is suggesting (Fig. 14.7).

1. the stability of the upper part of the citadel were several GPS sensor do not exhibit any movements; also archaeological structures seem to be relatively undamaged;
2. the continues rock falls in the S-W side of the cliff and related citadel's border, were also archaeological structure have been damaged by progressive

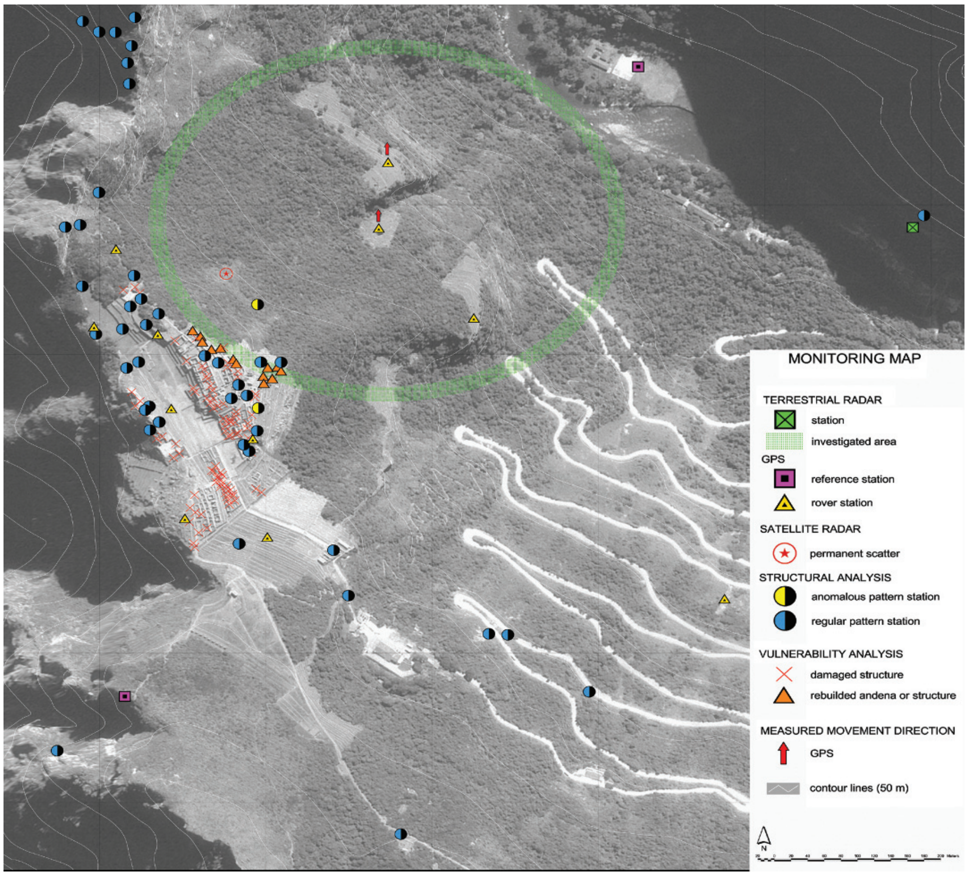

Fig. 14.7 Integrated map of surface deformation evidences and present monitoring data

lateral detensioning; this is probably the area with the highest short-term conservation problem.

3. the presence of a paleo-landslide in the North-East flank, with likely thickness of some tens meters, limited by a tension crack the discovering in 2004; in this area neither GPS nor PS nor JRC GBR-SAR detected any kind of deformation; in this area also structural geology detect some not regular pattern in the measurement.

Finally, the collected data are beginning to give a first picture of the slope evolution of the site. Nevertheless, the analysis of the monitoring data collected from the systems installed by Italian, Japanese and Czech-Slovak groups, together with data provided by Canadians and Peruvians, will allow a better evaluation of the mechanisms of slope processes and of landslides, leading to a complete harmonization amongst the observation of the different research groups involved.

As historical consideration, the data collected suggest the possibility that the site of Machu Picchu could have been selected by Incas also because of the availability of two large block deposits, useful for constructions: one on the so called "cantera" and the second in the paleo-landslide recently discovered.

Acknowledgements The present project has been found by the Italian Ministry of University and Scientific Research. Field activities greatly benefited fro the support of Istituto National de Cultural (INC) and INGMET.

References

Carlotto V. (1998). Evolution Andine et Raccourcissement au Niveau de Cusco (13–16°S) Perou. Mémoire H.S. 39, Université I de Grenoble, France, 203p.

Ferretti A., Prati C., Rocca F. (2001). Permanent Scatterers in SAR Interferometry, *IEEE Trans. on Geoscience and Remote Sensing*, 39(1), 8–20.

Hilley G.E., Bürgmann R., Ferretti A., Novali F., Rocca F. (2004). Dynamics of Slow-Moving Landslides from Permanent Scatterer Analysis, *Science*, 25 June 2004, 304(5679), 1952–1955.

Hutchinson J.N. (1988). General report: Morphological and geothecnical parameters of landslides in relation to geology and hydrogeology. Proc. 5th Int. Symp. on Landslides, July 1988, Lausanne. 1, 3–36.

Lancelot J.R., Laubacher G., Marocco R., Renaud U. (1978). *U/Pb radiochronology of two granitic plutons from the eastern Cordillera (Peru) — Extent of Permian magmatic activity and consequences*. Int. Journal of Earth Sciences, 67(1), 236–243.

Mazzoli S., Delmonaco G., Margottini C. (2005). Role of precursor joints in the contractional deformation of the granite pluton, Machu Picchu batholith, Eastern Cordillera, Peru. Rend. Soc. Geol. It., I (2005), Nuova Serie, 3 ff, in printing.

Sassa K., Fukuoka H., Kamai T., Shuzui H. (2001). Landslide risk at Inca's World Heritage in Machu Picchu, Peru. Proceedings UNESCO/IGCP Symposium on Landslide Risk Mitigation and Protection of Cultural and Natural Heritage, Tokyo, 1–14.

Sassa K., Fukuoka H., Shuzui H., Hoshino M. (2002). *Landslide Risk Evaluation in the Machu Picchu World Heritage, Cusco, Peru*. Proc. UNESCO/Kyoto University International Symposium on Landslide Risk Mitigation and Protection of Cultural and Natural Heritage. Kyoto, 469–488.

Sempere T., Carlier G., Soler P., Fornari M., Carlotto V., Jacay J., Arispe O., Neraudeau D., Cardenas J., Rosas S., Jimenez N. (2002). Late Permian-Middle Jurassic lithospheric thinning in Peru and Bolivia, and its bearing on Andean-age tectonics. Tectonophysics, 345(1–4), 153–181.