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A study of Japanese Landscapes using Structure from Motion Derived DSMs and DEMs based on Historical Aerial Photographs: New Opportunities for Vegetation Monitoring and Diachronic Geomorphology

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Keywords

Structure from Motion; Aerial Photographs; Photogrammetry; geomorphometry; GIS; diachronic analysis; remote sensing

Highlights

Using ‘Structure from Motion’ past geomorphic landscapes can be recreated;

Analysis of Geomorphic changes using aerial photographs;

‘Structure from Motion’ has to be used carefully as it can produce a 3D models that aren’t accurate;

Abstract

SfM-MVS (Structure from Motion and Multiple-View Stereophotogrammetry) is part of a series of technological progresses brought to the field of earth-sciences during the last decade or so, which has allowed geoscientists to collect unprecedented precise and extensive DSMs (Digital Surface Model) for virtually no cost, rivalling LiDAR (Light Detection and Ranging) technology. Previous work on SfM-MVS in geosciences has been solely exploring data acquired for the purpose of SfM-MVS, but no research has been done in the exploration of photographic archives for geomorphological purposes. Therefore, the present publications aims to present the usage of SfM-MVS applied to historical aerial photographs in Japan, in order to (1) demonstrate the potentials to extract topographical and vegetation data and (2) to present the potential for chronological analysis of landscape evolution. SfM-MVS was implemented on black-and-white and colour aerial photographs of 1966, 1976, 1996, 2006 and 2013, using the commercial software Photoscanpro®. Firstly, the photographs were masked, tied to GPS points; secondly the positions of the cameras and the 3D pointcloud were calculated; and thirdly the 3D surface was created. Data were then exported in the GIS software ArcGIS for analysis. Results also proved satisfactory for the reconstruction of 3D past-geomorphological landscapes in coastal areas, riverine areas, and in hilly and volcanic areas. They also prove that the height of trees and large vegetation features can also be calculated from aerial photographs alone. Diachronic analysis of the evolution in 3D landforms presented more difficulties, because the resolution of the early photographs was lower than the recent ones. Volume and surface calculations should therefore be conducted carefully. Although the method holds merit and great promise in the exploration of active landscapes that have widely changed during the 20th century; the authors have also reflected on the issues linked to large datasets, mostly because the processing of these large datasets is still in need of improvement. Moreover there is no proof that an ever increasing resolution brings any major advance to the geomorphological paradigms.

1. Introduction

Recent advances in computing capacities, and especially the development of multiple-core processors and the wide-distribution of the Intel IE7 processor, have brought to personal computers and small servers the calculation capacities necessary for applications such as complex nested fully-physical models (e.g. Gomez and Soltanzadeh, 2012) and 3D photogrammetric applications (e.g. Fonstad et al., 2013); two areas of earth-surface processes and landforms known to be technologically challenging and of increasing interest.

Relying on these technological advances, the photogrammetric method based on unregistered non-metric photographs, known as SfM-MVS (Structure from Motion and Multiple-View Stereophotogrammetry), has been spreading very fast, as attested at the last conference of the International Association of Geomorphology in Paris (2013) – session 26C on Geographical Information System, Spatial Analysis and Digital Elevation Models was dominated by applications using structure-from-motion and multiple-view-stereophotogrammetry.

Although the geosciences community is only starting to develop interests in SfM-MVS, the method isn't new as it was developed in the late 1970s in the field of computer vision (Ullman, 1979) and was then also referred to as 'structure and motion'. It has since developed into a valuable tool for generating 3D models from 2D imagery (Szeliski, 2010) and it has recently known a real expansion in the field of geo-sciences, mostly because of the development of software for non-specialists, such as Photomodeller, VisualSfM, or Photoscanpro – the last was developed by Agisoft and is being used in the present contribution.

SfM-MVS is a compound of two processes. The first one (SfM) consists in the reconstruction of a 3D pointcloud based on a series of overlapping 2D photographs, a common problem in computer vision. The specificity of SfM is its ability to simultaneously estimate the 3D geometry of a scene, while it also determines the pose of the camera. The computation of SfM only relies on image correspondences (Lowe, 2004). Therefore, using solely overlapping photographs, the algorithm recognises objects into the photographed scene, and then performs calculation based on the locations of the identified object. The computational process starts with (1) the retrieval of the position of each camera (in a non-referenced and unscaled 3D space), (2) the positioning in 3D of the identified features in the scene and (3) a bundle adjustment, which improves the relative positioning of the 3D-points (Lourakis and Argyros, 2009). This results in a 3D constrained space, but without a scale related to the reality and without a proper orientation. To resolve these two issues, it is possible to either enter position values in the 3D scene, taken from control-points – such as recorded DGPS point entered in the 3D scene – or from GPS/DGPS data linked to the camera. The GPS position of each photograph has the advantage of increasing the speed of data processing as it reduces the time necessary for step-1 but it is necessary to use a high-quality GPS or DGPS when working on scenes of small sizes. The second step concerns the reconstruction of a 3D mesh (vertices and polygons). Although it is possible to use the pointcloud created by means of SfM to directly create an interpolated mesh, MVS uses traditional photogrammetric technique adapted to multiple photographs to calculate a higher number of 3D points using the points calculated by SfM as the equivalent of control-points. The combination of the two techniques allows the development of multiple-photograph photogrammetry without the necessity of having numerous control-points in the field. This appears as a clear advantage for working in areas that are hardly accessible – providing that control-points can be collected in accessible areas, on the margins for instance – although the lack of points in the centre would increase the chances of errors; it also extends the possibilities of 3D reconstructions for areas that have changed and for which aerial or series of overlapping land-based photographs exist. Historical photographs, aerial photographs and the large amount of photographs taken by tourists and uploaded over the internet are a potential source of 3D geomorphological data, which haven't been explored yet.

Up to present, SfM-MVS research and applications have used photographs taken for the purposes of SfM-MVS (from UAVs or from the ground) and only Gomez (2013, 2014) has started to explore the geomorphological possibilities of existing archives. The development of the SfM-MVS technique using handheld non-metric cameras is relatively recent in geomorphology (James and Robson, 2012; Westboy et al., 2012) except for one early article, which began to explore the possibilities of the technique (Heimsath and Farid, 2002). James and Robson (2012) have shown the possibilities of the method at different scales, using its scale-invariant characteristics. Indeed, as SfM-MVS is only limited by the camera resolution,

one can explore very small to very large features. They reconstructed a volcanic bomb of a few centimetres in diameter, a volcanic crater of a few kilometres diameter and also at an intermediate scale, an outcrop. This work includes data acquisition in the manner aerial photographs are recorded, doing a 'flight over' a surface or circling around a small object. These two methods are the recommended methods for most of SfM algorithms to collect data for the reconstruction of surfaces developing over a plane and for discrete objects.

Researchers have also used flying platforms such as UAVs (Unmanned Autonomous Vehicles) or balloons equipped with standard cameras providing a resolution of 1 cm to 10 cm per pixel (Fonstad et al., 2013). Such an acquisition method is particularly adapted for the construction of DSM (digital surface model) and the extraction of topographic data. The development of the method for topographic investigation has seen a particular peak of interest in the field of archaeology and geo-archaeology, especially to produce 3D records of excavations (De Reu et al., 2014) or to record in 3D of archaeological objects (De Reu et al., 2013) and sites (Verhoeven, 2011).

Such popularity is due to the fact that it is an easy-to use and virtually free method, and it is also due to the results of experiments in the last years showing that SfM-MVS is extremely reliable as its results closely approach those provided by laser technologies such as TLS (Terrestrial Laser Scanner) and ALS (Airborne Laser Scanner) (Westoby et al., 2012, Obanawa et al., 2014).

As Westoby et al. (2012) discussed at the end of their manuscript, there are however several drawbacks to the method and it should not be considered as a silver bullet. Contributing to this discussion, the present article aims to test the suitability of SfM-MVS based on historical aerial photographs for the purpose of geomorphological and vegetation investigations. The authors will attempt to provide answers on whether it is possible to: (1) reconstruct past geomorphic features from historical aerial photographs, (2) use mathematical and geostatistical tool to correct the DSM and extract DEM (digital elevation model) data semi-automatically, and (3) perform measures from the 3D imagery including diachronic geomorphologic analysis.

2. Method

The present contribution relies on the usage of SfM-MVS extracted from historical aerial photographs of Japan for the period 1966 to 2013 at three different locations in Japan. The data are the freely available low-resolution aerial photographs, and a set of aerial imagery collected in the aftermath of the floods of 2013 by the GSI (Geospatial Information Authority of Japan). The dataset comprises photographs of 1966, 1976, 1996, 2006 and 2013. For the four first years, the photographs were recorded using the analogue Leica RC8, RC20 and RC30, while the photographs of 2013 were recorded using a digital UCX. The scale of the photographs ranges between 1/10000 and 1/30000 (Table 1). The data covers a variety of geomorphologic landscapes: a coastal hilly landscape in Yamaguchi prefecture, a river terrace landscape in Aizu; and an active stratovolcano, the Sakurajima in South Japan (Fig. 1).

Firstly, the suitability of historical aerial photographs for extracting topographic and vegetation data was investigated using the two first datasets of (1) Yamaguchi prefecture and (2) the West of Aizu basin along the Tadami-River floodplain (Fig. 1). The Yamaguchi prefecture is located on the West coast of Honshu Island, opening towards the Sea of Japan. The aerial photographs of Yamaguchi prefecture have been selected because of their challenging nature for SfM-MVS reconstruction. Indeed the presence of the sea limits the amount of data that can be generated along the coast. This is mostly due to the light reflecting over the water surface and to the presence of moving sea-waves, which do not offer any fixed point from which SfM can make calculation. The second challenge is related to the forested nature of steeply rising coastal mountains, which stand close to the littoral with an almost non-existent coastal plain. The only near-horizontal areas are the small pocket-beaches and the river estuaries. Also, the usability of diachronic series of aerial photographs was tested in a rapidly changing volcanic environment: the Sakurajima Volcano (Fig. 1). The Sakurajima Volcano is located in the South of Japan, at the southern extremity of Kyushu Island, near the city of Kagoshima. The volcano has been active through the 20th century, generating numerous modifications of the geomorphology (Gomez, 2014).

The first step of the data processing consisted in the extraction of DEM data and DSM data (topography and vegetation) from the aerial photographs. The latter were uploaded in the commercial SfM-MVS software developed by Agisoft: Photoscanpro®. For this first step, the procedure was as follows: (1) mask the inscriptions on the aerial photographs and all the moving objects that could induce errors in the calculation, such as clouds, boats, etc; (2) the camera position and orientation was used to constrain the proportion of the 3D scene, when the information was available (only for the 2013 photographs of Yamaguchi prefecture); (3) Known GPS control-points were added to the photographs with 5 to 14 markers per set of photographs, which were spread as regularly as possible over the study areas. The reader will note that for areas in the vicinity of the sea and active volcanic areas, these points were sparser. These points were set to provide the 3D model with an orientation and a scale. After these first pre-processing steps, a streamlined process in Photoscanpro® is: (1) reconstructing the 3D pointcloud and the position of the cameras; (2) transforming the pointcloud into a 3D surface using multiple-view stereophotogrammetry; (3) mapping the texture from aerial photographs over the 3D scene.

The second step of the data processing, was the extraction of a large mass of vegetation, which was extracted from the DSM to produce a DEM using a manual approach. Using the trees' height values found at the edge of the forest, this value was extracted in all the forested areas, making the assumption that the forest heights were homogeneous. Secondly an automated extraction using wavelet decomposition was performed applying the method in Gomez (2012), in order to remove the local variations linked to the presence of single trees, etc. The wavelet decomposition was performed using a Haar wavelet with 4 levels of decomposition. From this decomposition the authors extracted 'large-scale' features from the DSM, therefore reducing the effects of the micro-topography and the land-cover variations.

3. Results: SfM-MVS and Historical Aerial Photographs for different geomorphologic settings

The first section of the results presents the usage of historical aerial photographs to work on geomorphology and vegetation morphology. The second section concentrates on the Sakurajima Volcano and the diachronic evolution of the landscape between 1966 and 2006 using solely SfM-MVS for a photogrammetric acquisition of the 3D data.

First, the suitability of SfM-MVS was tested for the coastal mountains of Yamaguchi prefecture. The official DEM generated by the GSI and the DEM created by SfM-MVS were first compared. A first test was performed along three topographical transects (Fig. 2). Transects 1 and 2 begin at sea level and end at topographic highs in the coastal mountains, while the third transect goes across the littoral plain (Fig. 2). The transects from the two compared DEMs show similar topographical behaviours with three mounts separated by three valleys, although the SfM-MVS derived DEM shows numerous localised variations – their origin is discussed later on. Despite these similarities, the three transects differ at high-altitude, as the maximum topography at 2.5 km distance reaches 250 m for the SfM-MVS derived transect 1 and only 178 m for the DEM from the GSI (Fig. 2-D). Profile 2 and Profile 3 (Fig. 2-E & F) display the same tendency to increase maximum positive values as the respective topographic maxima compute 175 m against 140 m and 107 m against 70 m. For SfM-MVS derived DEMs, this error is very pervasive, because the general appearance is in accordance with the topographic trends (Fig. 2 B and C) as the linear regression between both datasets displays a $R^2=0.965$ and an equation $a=1.367*x - 14.22$ (a: the SfM-MVS derived values and b the GSI-DEM values). Moreover, areas near sea level are characterized by a greater accuracy and the error is not spread evenly through the dataset.

Although, the DSM of the Yamaguchi coastal area was manually cleaned from vegetation the DEM produced using SfM-MVS and manual vegetation extraction was then reprocessed with wavelet decomposition – as explained in the method – in order to remove all the micro-variations that may hamper the quality of the dataset. This method has also allowed the authors to convert the SfM-MVS based DEM into a DEM of the same resolution as the GSI-DEM, for which each cell is 10 m x 10 m. The filtering of these horizontally short-lived and vertically limited (<10m) variations provides a DEM that is closer to the GSI-DEM (Fig. 3-B). Following the linear relation between the two datasets improved with the filtered DSM (Fig. 3-C), the relation displays a R^2 of 0.97 along an equation: $1.02*x - 5$, improving the relation between the two datasets. This first part of the analysis shows that even in environments that are difficult for SfM-MVS – covered in vegetation and in coastal area - it is possible to reconstruct the topography although the DEMs are less suitable for geomorphometry than for general geomorphological analysis.

The second area investigated, in order to understand the usability of SfM-MVS for biogeomorphometry, was the floodplain of the Tadami River, North of Numazawa Volcano. For this DSM, the vegetation wasn't removed as the principal goal was to investigate the possibility of detecting and measuring vegetation using SfM-MVS (Fig. 4). The site of the floodplain of the Tadami-River provides another type of geomorphological landscape, for

which SfM-MVS combined with aerial photographs can be very useful: the evolution in 3D of a riverine environment. The large amount of open-fields and the limited amount of forested mountains allowed a regular distribution of control-points providing a framework in which the problems of the forested coastal area were not encountered, even if the reflections of the river water surface created local errors on the water surface (Fig. 4-C). Providing that the SfM-MVS derived dataset is linked to control-points in the landscape, historical aerial photographs can offer an instantaneous view of the landscape and the geomorphology at a precise given date, and especially at a time when no precise topographic data or vegetation inventory were available. Such dataset can then be decomposed between topographic variations and vegetation micro-variations and signal noise using decomposition techniques such as wavelets (Fig. 5).

Active volcanoes are an interesting research area for diachronic analysis as they are in constant and rapid evolution, even at the historical time-scale. For the year 1966, a series of black-and-white aerial photographs was used to work on the volcanic geomorphology and map the different landforms. Using aerial photographs, the reconstructed topographic data allow a better understanding of the landforms and can help drawing geomorphological maps (Fig. 6). Based on the reconstructed DEM (Fig. 6-A) and the aerial photographs mosaic (Fig. 6-B), the geomorphological map of the volcano (Fig. 6-C) provides confirmation of the slope orientations and variations that are observable from aerial imagery. From this dataset, one can observe that the Sakurajima has the typical conic shape of stratovolcanoes. Its slopes are dominated by a series of lava-flow deposits that radiate from the upper slope. They are easily recognizable by the presence of stress-lines perpendicular to the original flow direction. This general structure is however irregular, with a large-erosion feature to the North, characterized by steep upper-slopes (Fig.6 – C) and a large lobate deposit at the bottom (in both Fig. 6-C and Fig. 7). The upper-slopes are covered by a fine pyroclast drape, and a similar smooth-pseudo-horizontal surface also extends to the East (Fig. 6-C), which can be assigned to pyroclastic-flow and lahar deposits. At the summit, two vents are aligned along a North-South axis (Fig. 7). One can also observe that within the main vent, there is a second smaller vent, with a topographical flat. On the eastern lower flank of the volcano, another large vent opens to the East. If SfM-MVS allows the scientist to work on the intricacies of the volcanic morphology – in this case in 1966 -, it also allows the reconstruction of the volcanic evolution, through a diachronic analysis using photographic datasets at different periods (Fig. 8). For the Sakurajima Volcano, using a series of diachronic 3D models (Fig.8) and aerial photographs mosaics reconstructed using SfM-MVS, the authors have successfully rebuilt the 3D landscape of the Sakurajima of 1966, 1996 and 2006, proving that historical aerial photographs have great potentials for the analysis of 3D diachronic evolution.

4. Discussion

The present study has shown that historical aerial photographs are promising material for the reconstruction of past-historical environment and geomorphology and that even vegetation characteristics like tree height can be extracted, and eventually monitored over long periods of time, unveiling new possibilities in the fields of biology and biogeography. It also

confirms conclusions of James and Robson (2012) who wrote: “SfM-MVS approach can produce surface or topographic data over scales and scenarios relevant to a broad range of geoscience applications”. Using time-series of photographs taken from the end of the WWII, SfM-MVS also provides an opportunity to build landscape 3D archives, following the evolution of the landscape (Gomez, 2014). As the present work was carried out using freely available aerial photographs that are mostly 200 dpi (except for the colour photographs of 1976 North of Numazawa Volcano that are 400 dpi), there is therefore room for improvement in term of accuracy and precision using high-resolution aerial photographs.

Indeed, the resolution of the aerial photographs plays an important role in SfM-MVS with regard to the precision and the possibility of applying the method successfully. Aerial photograph series of low resolution generate difficulties for the edge-recognition used to identify objects in photographs and subsequently the positioning of these objects in 3D. However, a large number of pixels (e.g. >12 millions per image) does not guaranty an accurate reconstruction in 3D either (Westoby et al., 2012) and it has many detrimental effects such as highly increased computation time. Most importantly, the number of overlapping images plays a significant role in the accuracy of the 3D reconstruction. Westoby et al. (2012) have demonstrated that the accuracy is highly correlated with the density of points generated by SfM. For an area of 160 m x 160 m, they recorded variations between SfM-MVS pointclouds and TLS pointclouds of up to positive 3 m and negative 3 m. They also noted that areas of dense vegetation generated the highest discrepancies, as for the forested case-studies presented in this contribution. Another source of error, that wasn't an issue in other studies (Fonstadt et al., 2013; Westoby et al., 2012), is the quality of the images: blurred, or dark pictures, or photographs taken with a veil of haze in the sky. As these aerial photographs were not taken for the sole purpose of SfM-MVS, they can present several challenges, and experience has shown that it is better to have fewer but crisper pictures, rather than a large number of blurred and/or dark pictures. A way to overcome these issues, if they are limited to portions of the image is to crop the unwanted parts is also an effective way to handle these issues.

SfM-MVS presents intrinsic limitations, if not dangers. Indeed, software packages such as the one developed by Agisoft can produce, almost without fail, a 3D surface that mimics reality, but only experience and experiments against datasets acquired using other techniques can reveal the limitations and the errors in the datasets (Fonstad et al., 2013). In Fonstad et al. (2013), although the authors have shown that the vertical elevation of the LiDAR points and the SfM points have a correlation coefficient of 0.971 and a RMSE of 1.049 m, the difference between the Lidar data and the SfM can range from 1.5 m to 6.56 m in Z, especially for water areas with irregular light reflection, and from 1.5 to 10.5 m for areas under vegetation cover.

Nevertheless, SfM-MVS is one more step towards more standardisation of high-resolution DEM data acquisition, which has become even cheaper and widespread during the last decade. With such large datasets, questions of their usability and necessity arise. What do we gain from such high-resolution datasets and how can they be processed. High-resolution data have obvious advantages for calculating accurate volumes or modifications in the landscape at a resolution never attained before, but the real question is to determine if one can derive new ways of working from these datasets or if we are just applying the same method, but at a higher resolution. Indeed, one of the issues with the over-specialisation in sciences and the

race towards more accuracy is the difficulty of developing new concepts and using the ever increasing datasets in new and creative ways.

The question of the usability of these datasets is another issue the scientist has to overcome. Persendt and Gomez (2015) have been developing a GIS-based hydrological algorithm to work from LiDAR data in the Cuvelai Basin (Namibia), because the high-resolution LiDAR data were generating errors in the water-flow routine, which were developed in the last decades of the 20th century when such high-resolution datasets were less common. Therefore, it appears that the challenges for earth-surface scientists have now shifted from data collection - and the problem of collecting sufficient data for it to be significant - to data processing and usage in appropriate algorithms.

Conclusion

The combination of aerial photography and digital photogrammetry based on structure from motion opens interesting avenues to explore landscape evolution from the mid-20th century to the present, especially in very active geomorphic areas, such as river, shore, and volcanic environments, especially when no or only poor topographical data exists. While this work contributes to recent developments in geomorphology and applied SfM-MVS (Westoby et al., 2012 and Fonstad et al., 2013), the novel ideas are the exciting potentialities around diachronic analysis of vegetation, topography and landscape evolution through the 20th century.

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Figures caption

Fig. 1 Locations of the three different study sites in Japan. The choices of the different sites was motivated by their geomorphological diversity, one being in riverine setting (the site in Fukushima Prefecture), one being in a coastal setting (the site of Yamaguchi prefecture) and one being an active volcano (the site of Kagoshima Prefecture).

Fig 2: Comparison between the topographic data calculated using SfM-MVS and the data of the GSI. This data was created with control points at 0 m a.s.l., but without adding any point in the high topographic high-points. Although the topographical behaviour is consistent with the data of the GSI, it appears that there is a scaling problem for the high-topographic points. (A) Georectified orthophotograph of the study area – 2006; (B) DSM (Digital Surface Model) generated by SfM-MVS; (C) Interpolated DEM (Digital Elevation Model) from the GSI; As the intention is comparison of profiles from the two DEMs, the paired profiles should be superimposed, with the simpler (GSI) one dashed.

Fig. 3 Comparison method of the GSI-DEM dataset and the SfM-MVS derived DSM, transformed using wavelet decomposition (with Haar wavelet) in order to limit the impact of vegetation and provide a resampled framework for comparison between the two datasets. (A) Extracted DSM and DEM of a valley. The enlargement provided allows a better understanding of the variations between the two datasets; (B) Original topography and landcover transect and its decomposition using Haar wavelet (4 levels) in order to reduce the effect of the vegetation and eliminate small-scale vertical and horizontal variations. This denoising of topographic data was developed for volcanic purposes (Gomez, 2012); (C) Linear correlation between the GSI DEM dataset and the SfM-MVS based DSM after wavelet processing, using only the level (a).

Fig. 4 Geomorphology of the Tadami River floodplain to the North of Numazawa Volcano near the confluence with the Aga River flowing to the East towards the Aizu basin. (A) Reconstructed orthophotograph using SfM-MVS for the 1974 aerial photographs of the GSI; (B) DSM (Digital Surface Model) reconstructed using SfM. The reader will note that it isn't a

DEM (Digital Elevation Model) as vegetation is also represented and would need to be subtracted to obtain the DEM; (C) Enlargement on the errors produced by the river water reflections creating elevation artefacts.

Fig. 5 Transects across the Tagami River terraces. The topography was reconstructed using SfM-MVS, producing a DSM, therefore trees on the edge of the terraces also appear on the outcrops. (C: position of the channel; f1 and f2 depict the potential position of two fault scarps in the landscape. The presence of f1 was confirmed during private conversation with Assoc. Prof. K. Kataoka of Niigata University and its presence imaged by GPR by C. Gomez and K. Kataoka (unpublished material))

Fig. 6 DSM, Stitched Orthophotograph and Geomorphological Sketch of the Sakurajima Volcano built from the SfM-MVS derived method. The active Sakurajima Volcano offers a wide variety of geomorphological landscapes built from lava-flow deposits, pyroclastic-flow and lahar deposits and ash deposits.

Fig. 7 Topographic transects on the Sakurajima Volcano. Such transects are a precious tool to work on the deposits, slope, etc. evolution from 1966; (c) location of a potential slope-collapse; (d) location of a smaller vent inside the main vent presently active with a topographical flat.

Fig 8 Using ground-controlled aerial photographs from 1966, 1996 and 2006, the SfM-MVS method has allowed the reconstruction of the volcanic landscapes of the last 40 years. This method is especially useful for active volcanoes, which are known to evolve rapidly.

Table Caption

Tab 1 Characteristics of the photographs used for the different SfM-MVS case study.

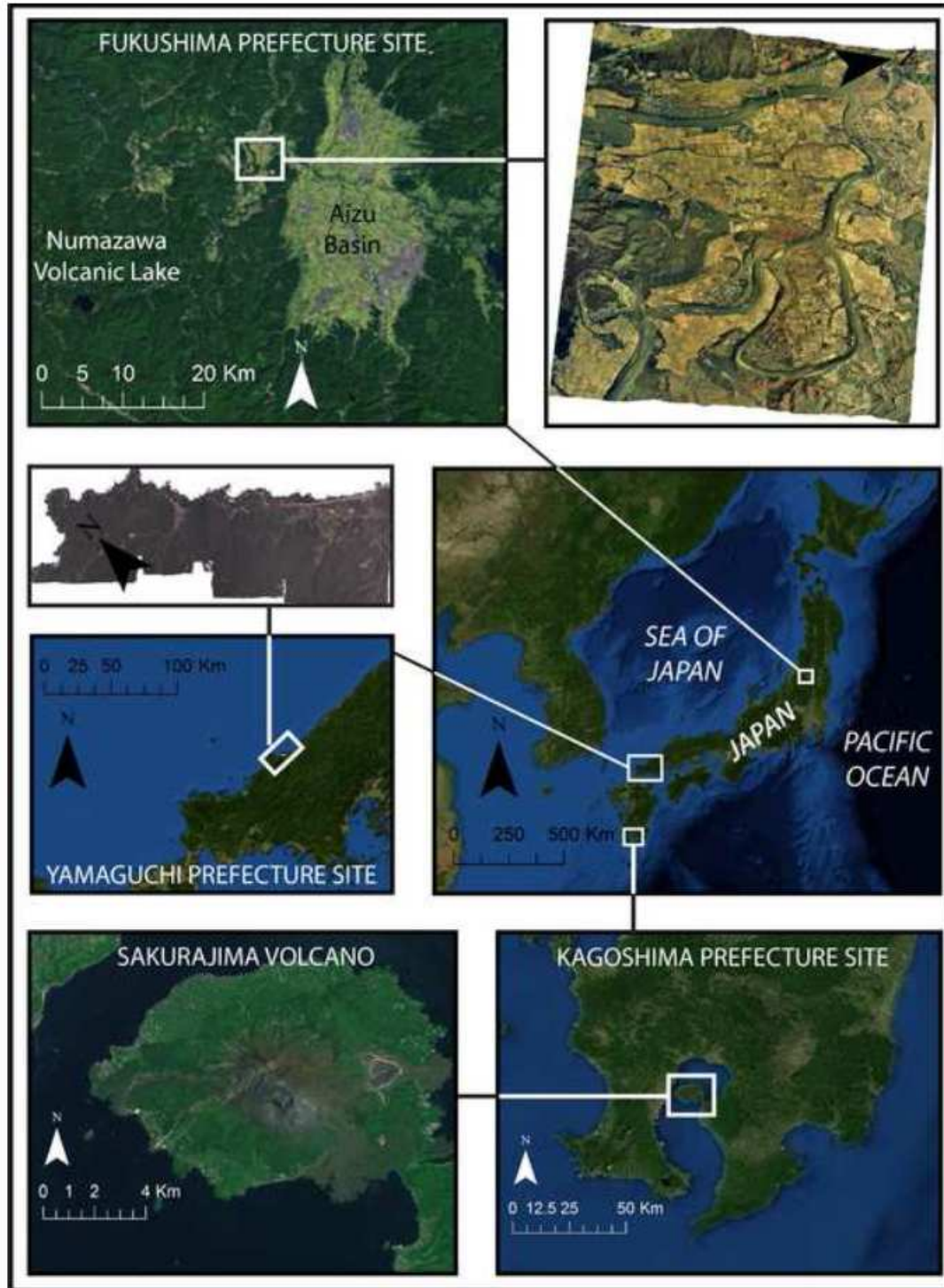


Figure 1

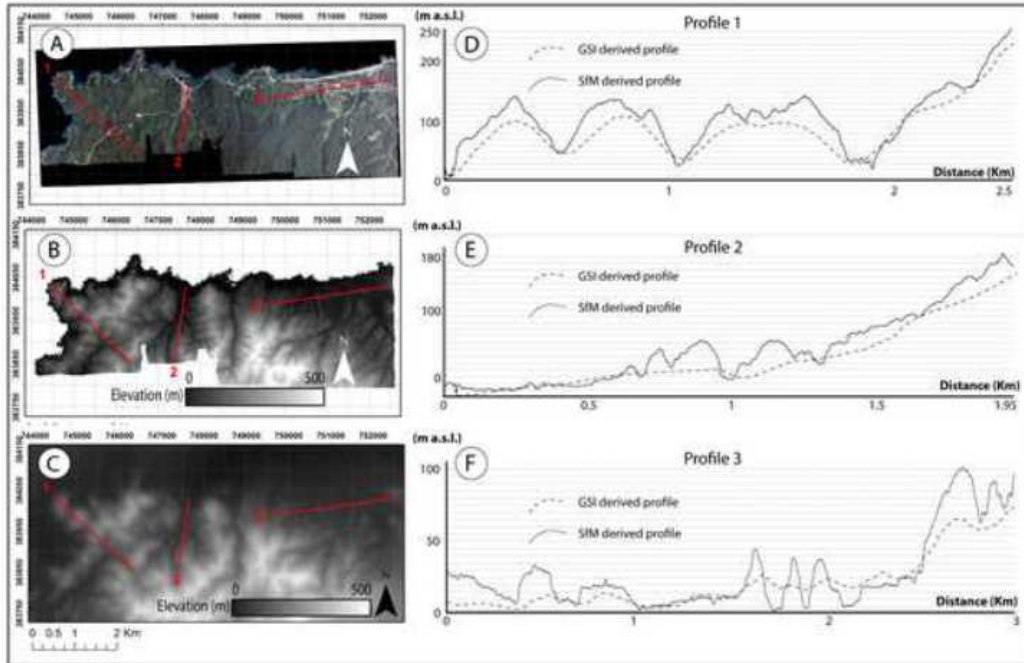


Figure 2

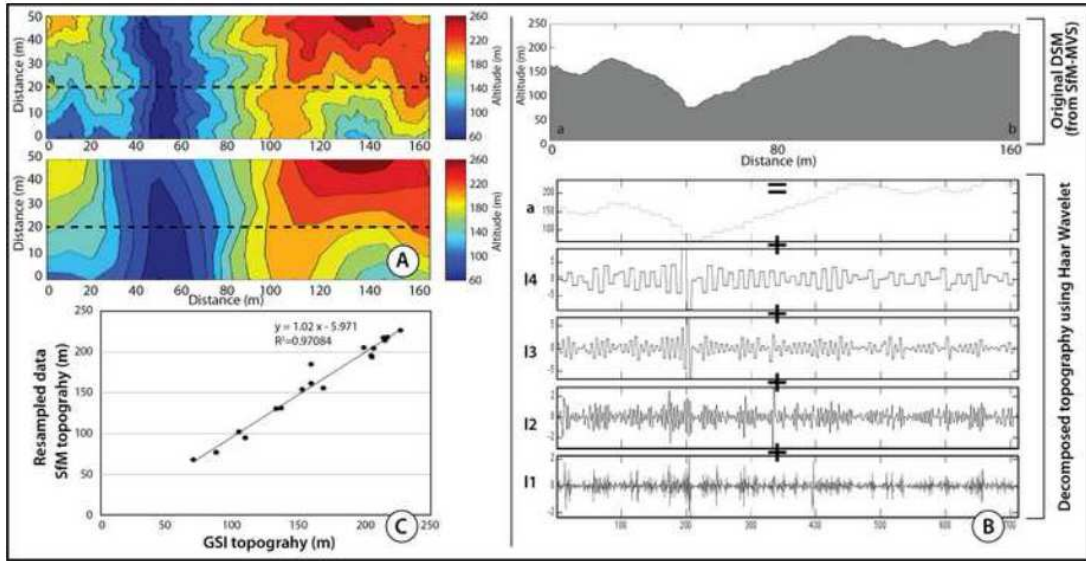


Figure 3

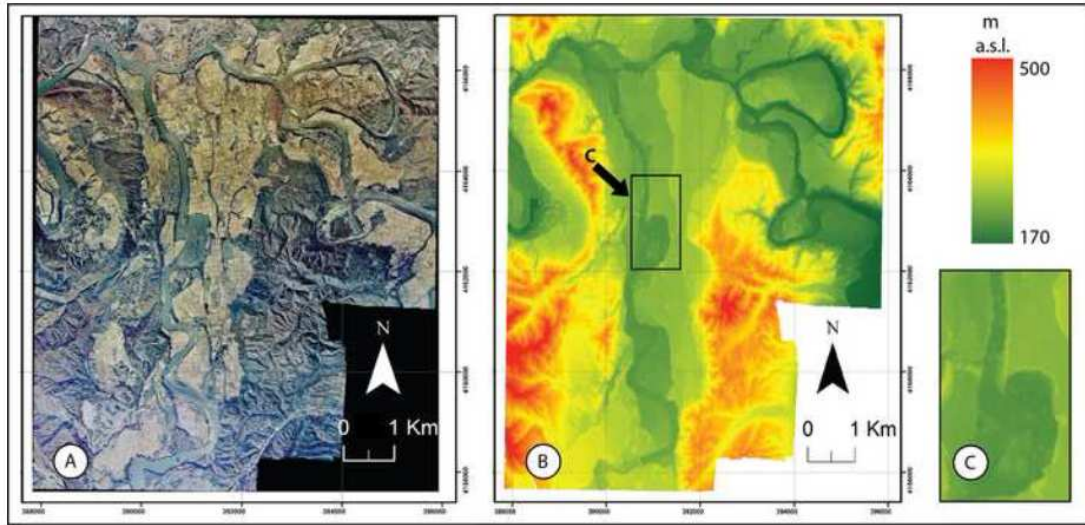


Figure 4

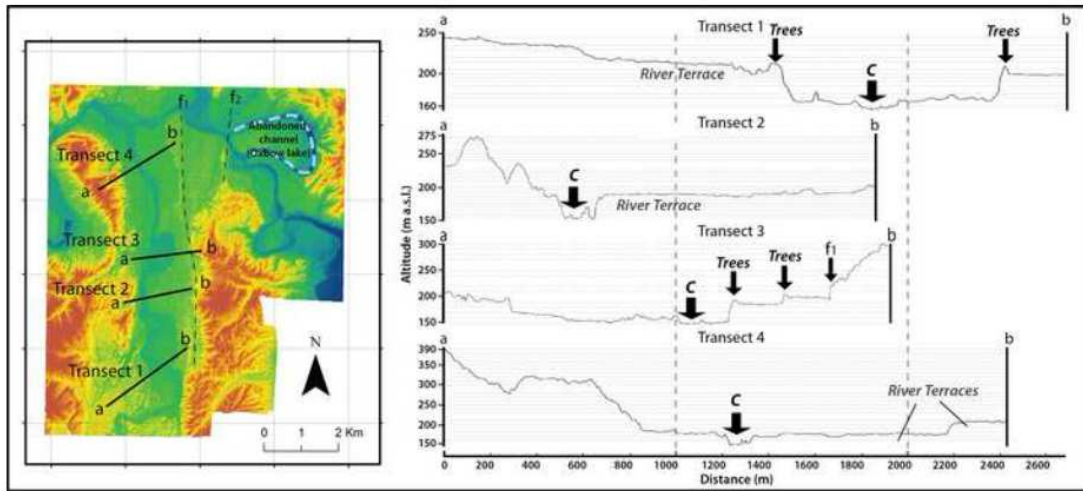


Figure 5

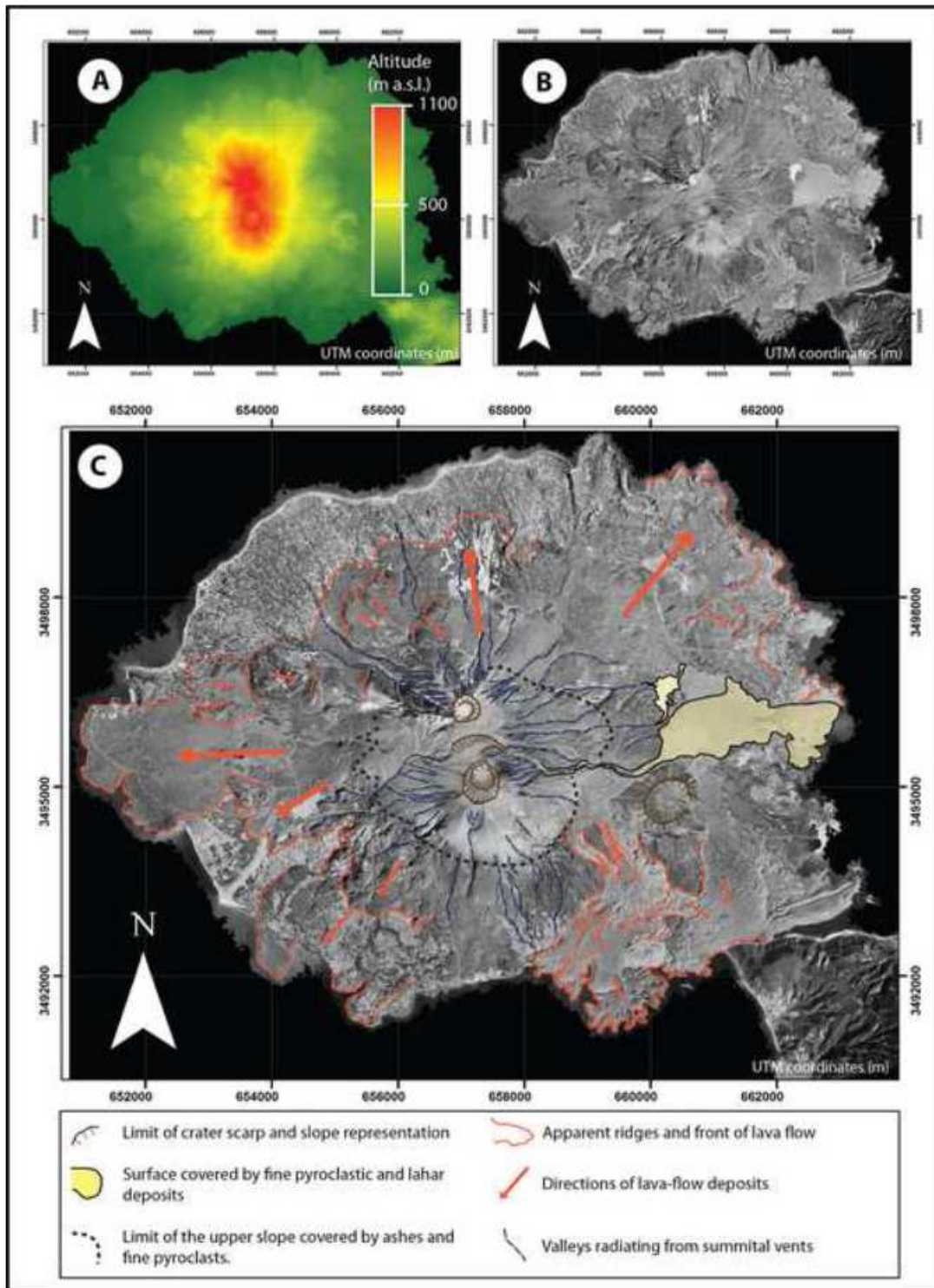


Figure 6

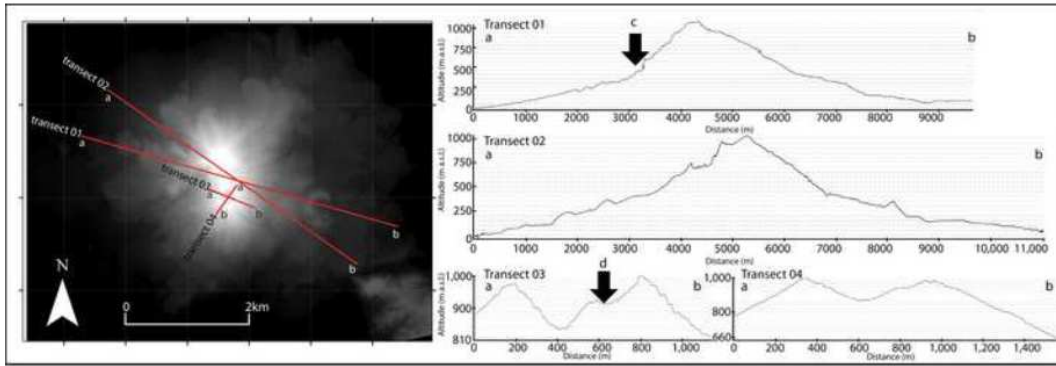


Figure 7

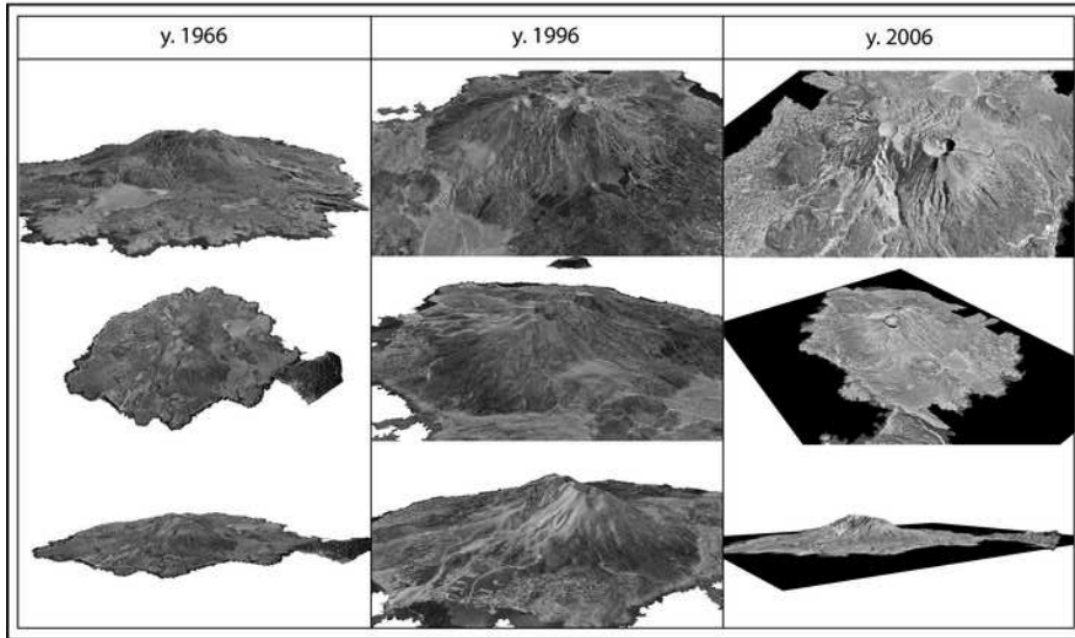


Figure 8

Table 1

Location	Sakurajima	Aizu	Sakurajima	Sakurajima	Yamaguchi
Year	1966	1976	1996	2006	2013
Flight elevation (m)	3500	2000	3900	4600	3651
Scale of the photograph	1/20000	1/10000	1/25000	1/30000	1/13000
Camera	Leica RC8	Leica RC8	Leica RC20	Leica RC30	UCX
Camera type	Analogue	Analogue	Analogue	Analogue	Digital
Photograph	Black and White	Color	Black and White	Black and White	Color
Number of photographs used	36	64	34	21	27

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