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# MULTI-DISCIPLINARY INVESTIGATIONS OF ACTIVE FAULTS IN THE JULIAN ALPS, SLOVENIA

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**ABSTRACT**
UK-Slovenian collaborative research connected to EU COST-Action 625 began in 2003 and has involved interdisciplinary research into the current activity, structural architecture and landscape expression of the Ravne and Idrija strike-slip fault systems in NW Slovenia. The Ravne fault may be the best exposed actively propagating strike-slip fault system in Europe and through combined structural fieldwork, earthquake seismology and airborne LiDAR (Light Detection And Ranging) surveys, a new understanding of the fault's along-strike segmentation, three dimensional geometry and stepover zone kinematics has been gained. The Idrija Fault in contrast, is poorly exposed, but defines a regional lineament with an intensely brecciated fault core; it may have been responsible for the largest historical earthquake to have ever affected the region. High-resolution LiDAR images recently obtained for both fault systems allow for efficient focussed fieldwork and future work will be devoted to documenting the timing of previous earthquakes and the connectivity and displacement transfer between active faults at the NE corner of the Adria microplate.

**KEYWORDS:** Strike-slip fault, active tectonics, Slovenia, Julian Alps, LiDAR

## INTRODUCTION

UK participation in COST-ACTION 625 has involved a collaborative research project in Slovenia with Slovenian geoscientists. The project is currently in progress and in mid-stage. Therefore, the end of the COST-Action does not coincide in time with the end of our research, which is growing and now leading to interesting results. This paper therefore represents a progress report summarising our results to date and our planned future activities.

## OBJECTIVES AND PARTICIPANTS

The purpose of our project is to better understand the active fault systems of NW Slovenia and processes of fault propagation, earthquake nucleation, and displacement transfer between the Dinarides and SE Alpine mountain chains (Fig. 1). Ultimately, the results of our research will allow a better understanding of the network of active faults and potential earthquake hazards in the region. The project principally involves Dickson Cunningham (Structural Geologist/Tectonicist University of Leicester, UK), Kevin Tansey and Stephen Grebby (Remote Sensing Specialists, University of Leicester), Andrej Gosar (Earthquake Seismologist and Head of Geophysical Monitoring Service of the Environmental Agency, Slovenia), Stanka Šebela and Janez Mulec (Karst Geologists, Karst Institute of Slovenia) and Vanja Kastelic (Structural Geology PhD Student, University of Ljubljana).

## PROJECT SIGNIFICANCE

The project is noteworthy for the following reasons:

1. The study is focussed on two major fault systems, the Ravne and Idrija Faults that help define the active diffuse NE plate boundary of the Adria microplate. Therefore, the study region affords an excellent opportunity to document processes of indentor corner tectonics; specifically, the manner in which strike-slip displacements along the Dinaride margin are accommodated by oblique transpressional deformation and thrusting in NW Slovenia and adjacent areas of the Italian Friuli Alps.

2. Two major earthquakes actually occurred on the Ravne fault system during the period of the COST-Action (Bajc et al., 2000; Gosar et al., 2001; Aoudia et al., 2005). Thus we have the opportunity to study a very seismically active fault system, which is propagating through mountainous terrain.
3. Our LiDAR (Light Detection And Ranging) surveys are the first attempts to use LiDAR to map active faults in Europe and the first attempts anywhere to survey high-relief mountainous terrain. This ground-breaking method provides impressive topographic detail that allows identification of subtle fault features, including scarps and displaced landforms. The LiDAR data can be used to identify fault scarps that could be trenched for paleoseismological analysis to assess future earthquake probabilities. Key results of our LiDAR surveys were recently published (Cunningham et al., 2006). More processing of the LiDAR data is planned for 2006-7 to optimise information output.
4. The rugged terrain along the Ravne Fault provides exceptional 3D exposure of main fault segmentation, antithetic and synthetic faults, fault bends, and fault rocks. Very few strike-slip faults anywhere in the world provide such informative exposures because strike-slip faults are commonly expressed as linear troughs that are covered by sediments and/or vegetation.
5. The largest historical earthquake to have affected the region was the 1511 Idrija earthquake which was responsible for 12,000 deaths (Ribarič, 1979; Fitzko et al., 2005). However, the fault that caused the earthquake is unclear. It is likely that either the Ravne or Idrija fault was responsible for the event and it is hoped that further study of both fault systems will help resolve the problem.

## METHODS

The research to date has principally involved detailed seismological analysis of the 1998 and 2004 Ravne Fault earthquakes in the Bovec/Kobarid region (Gosar and Kastelic), structural field studies along the Idrija and Ravne Faults and adjacent areas (Cunningham and Kastelic), and LiDAR mapping of the Idrija and Ravne faults (Cunningham, Gosar, Tansey and Grebby). TM-71 fault monitoring (Šebela, Mulec, and Gosar) is not part of the UK activities, but is allied research relevant to the project.

## FUNDING, RESEARCH SYNERGY AND PROJECT EXPANSION

In 2002, Dickson Cunningham received a UK Royal Society small grant to carry out initial field investigations into the structural geology of the Idrija and Ravne faults. Initial collaboration between Cunningham, Gosar and Šebela led to a successful Slovenian grant application to fund Kastelic's PhD project on the structural geology and earthquake seismology of the Ravne Fault. In 2003, Cunningham successfully applied to the Natural Environment Research Council for aerial LiDAR surveys to be flown of the Idrija and Ravne faults to map their surface expression at high resolution. In addition, in 2004, Gosar and Sebela initiated a monitoring project of the Idrija and Ravne faults using TM-71 instruments in collaboration with other COST-Action scientists from the Czech Republic. In 2005, Stephen Grebby and Kevin Tansey at the University of Leicester remote sensing unit joined Cunningham for the purposes of processing and interpreting the LiDAR data. Further fieldwork by Cunningham and Kastelic is planned and the LiDAR processing will continue through 2007.

## MAJOR RESULTS

### *IDRIJA FAULT FIELD RESULTS*

The Idrija Fault defines the longest lineament in NW Slovenia and can be traced for over 120kms. The fault cross-cuts older SW directed thrust sheets and strongly influences the modern drainage systems, but is poorly exposed. Efforts to locate fault exposures proved frustrating until the LiDAR survey data were processed and faulted outcrops were discriminated on the imagery near Kapa (Fig. 1a, inset map). Field checking of these outcrops revealed a 30 metre-wide zone of pervasive brecciation within limestones. The rocks are intensely shattered and form easily eroded gullies with crumbly unstable surfaces (Figs. 1c, d). Much of the fault material is loose breccia fragments and gouge. Near-vertical to steep NE dipping sheared surfaces and subtle striping of the outcrop surfaces due to differential fluid alteration suggests a near vertical to 80ºNE dipping fault core zone. On the margins of the fault zone, more coherent limestone outcrops occur which contain heavily fractured surfaces. Slickenlines on these surfaces are consistently horizontal to subhorizontally plunging and trend 300º.

### *IDRIJA FAULT LIDAR RESULTS*

The LiDAR ground surface models reveal that at Kapa, the Idrija Fault consists of a 50-150m-wide corridor of topographically rough terrain which is the surface expression of fault brecciation and gouge development, (verified in the field). In contrast, outside of the fault zone, the unfaulted ground surface is much smoother. This suggests that LiDAR may be a good tool for discriminating surface fault zones simply by their textural expression. The fault zone is continuous along strike, however discrete fault segments are identifiable as distinct linear surface traces. Geomorphic indicators of active tectonism revealed on the LiDAR along the Idrija fault near Kapa include uplifted and perched stream terraces, a beheaded stream valley, dextral stream offsets, and a faulted fluvial terrace (Cunningham et al., 2006).

Further analysis of the LiDAR data is planned, particularly with respect to mapping landslips along the Idrija Fault valley which may be products of older earthquakes along the fault system. In addition, the faulted fluvial terrace near Kapa will be evaluated for its suitability as a palaeo-seismological trench site.

### *RAVNE FAULT FIELD RESULTS*

Detailed investigations of the structural geology of the Ravne fault are a significant component of V. Kastelic's PhD thesis which is in progress; the results are beyond the scope of this report. However, preliminary results of several field visits by the first author confirm the importance of the Ravne Fault as a major dextral strike-slip fault that is actively propagating northwestwards through the alpine carbonate thrust stack of the Julian Alps (Fig. 2). Excellent exposures of the fault zone occur in the Krn Massif in the Planina na Polju area (Figs. 2b, c, e) and at the NW and SE ends of the Tolminka Springs Valley (Figs. 2a, d). The fault zone consists of discrete segments, sub-km scale releasing steps and numerous brittle splays. In addition, adjacent limestone beds are downturned into the fault zone either suggesting that strike-slip displacements have been accompanied by components of contractional deformation producing a flower structure fault and bedding geometry or that the fault reactivates a previous discontinuity. Where the fault plane is exposed, it typically is a 10-50 metre-wide damage zone containing vertical to steep NE dipping fault planes. Slickenlines and mullions are subhorizontal to horizontal in plunge (Fig. 2c).

The Tolminka Springs basin is a transtensional basin that has formed along the Ravne Fault (Fig. 1a inset map and 3). Normal fault scarps define bounding cliffs on the NE and SW sides of the basin and several other faults appear to deform the floor of the basin (Cunningham et al., 2006). Chaotic landslide deposits fill the centre of the basin whereas the northwest end is infilled by a large coarse alluvial cone. A single drainage exits the basin and has eroded a deep gorge which drains the valley. The Tolminka Springs Basin is an unusual tectonic feature in the Julian Alps because it is the product of localised transtensional deformation within an overall high-relief contractional and dextral transpressional orogen.

### *RAVNE FAULT LIDAR RESULTS*

The Ravne Fault LiDAR data reveal faults that enter and deform the Tolminka Springs transtensional basin in unprecedented detail. The data also provide a much clearer understanding of the depositional history of the basin and the links between tectonics, geomorphology, co-seismic landsliding, erosion, and sedimentation. The LiDAR images reveal basin bounding faults, individual fault traces, subordinate splays, possible scarps on the basin floor, antithetic faults in the ridges that bound the basin, and other brittle fracture sets probably associated with transtensional deformation (Cunningham et al., 2006; Fig. 3). Shaded relief models illuminated from different angles and directions provide informative perspectives on the links between fault scarps and development of the high-relief landscape. Further processing of the LiDAR data SE of the Tolminka Springs Basin is planned to map the southeast continuation of the fault system which is poorly resolved on normal air and satellite images.

### DISSEMINATION OF RESULTS

Key results of the application of LiDAR data to mapping the Idrija and Ravne Faults were published in Geophysical Research Letters in 2006 (Cunningham et al., 2006). A paper by Kastelic and others on the detailed structural geology of the Ravne Fault and the propagation geometry and kinematics of the 2004 and 1998 earthquakes is also in progress.

Scientific presentations on the status and results of the project have been made at the Sofia, Granada, Bratislava, Wroclav and Florence COST-Action meetings and Kastelic and Cunningham presented results at the annual Tectonic Studies Group Meeting in Manchester in January, 2006 and at EGU in Vienna in April, 2006. Tansey and co-authors presented new Slovenian LiDAR data at the 2006 Remote Sensing and Photogrammetry Society Annual Conference, during September 2006 in Cambridge, UK. In 2007, the results of the LiDAR surveys will be presented at the annual Tectonic Studies Group Meeting in Glasgow in January, and at EGU in Vienna in April.

### CONCLUSIONS

To summarise, initial contacts made at the COST-Action 625 Camerino meeting in 2003 led to a successful Royal Society grant, a NERC funded airborne LiDAR survey, and a funded PhD and MSc project. The project now has seven major participants and represents a successful international collaboration that is a direct outgrowth of COST-Action 625. Future work will build on initial results and will involve further structural fieldwork at key locations, more processing of LiDAR data, palaeo-seismological site investigations, and possibly quantitative analysis of the tectonic geomorphology associated with both fault systems.

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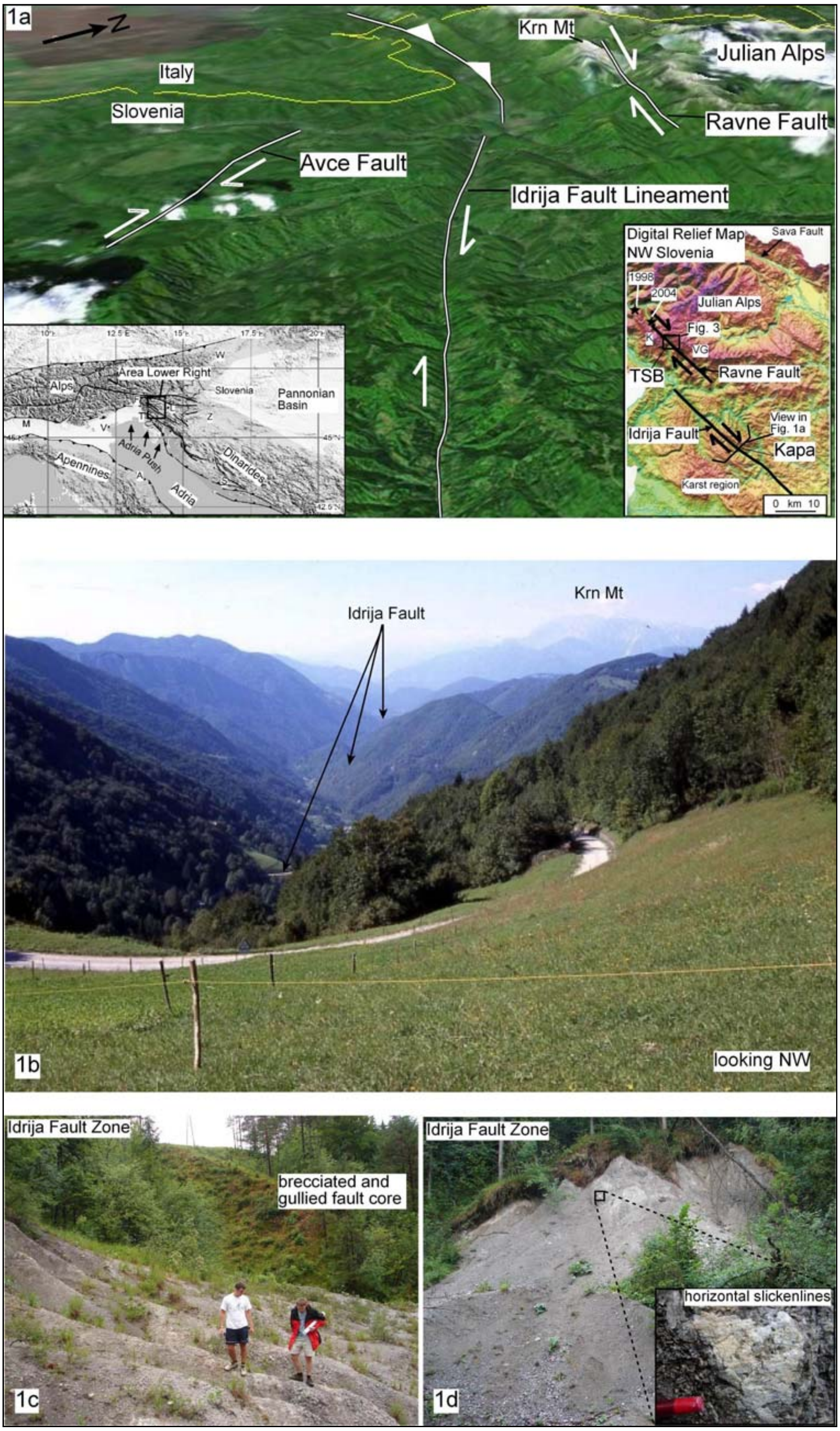


**Fig. 1**

a) GoogleEarth oblique NW view of Idrija, Ravne and Avce dextral strike-slip faults that help define the NE diffuse plate boundary of the Adria microplate. Inset map lower left shows location of study area in NW Slovenia in context of Alpine orogen and Adria indentor. V: Venice; A: Ancona; T: Trieste; L: Ljubljana; Z: Zagreb; S: Split; M: Milan; W: Vienna; F: Friuli. Inset lower right shows location of Ravne and Idrija Faults, 1998 and 2004 earthquakes, and subsequent figures. K: Krn Mountain; VG: Vogel Mountain; TSB: Tolminka Springs Basin.

b) View NW of Idrija Fault valley.

c) Gullied outcrops of inner damage zone for Idrija Fault consisting of intensely brecciated limestone at Kapa.

d) Fault exposure at Kapa showing crumbly shattered nature of fault breccia. Inset shows horizontal slickenlines on sheared surface within breccia zone.

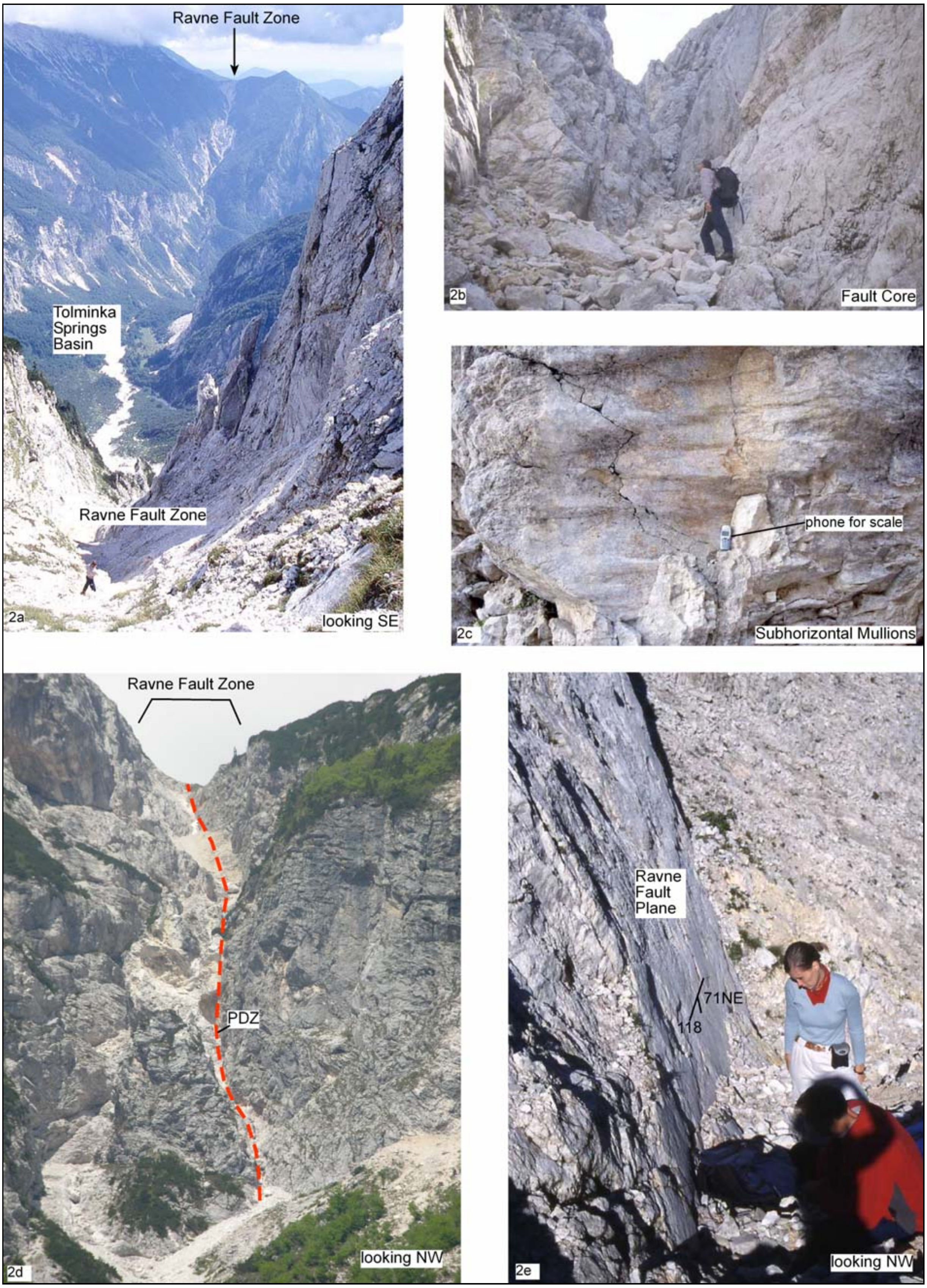


**Fig. 2**

a) View SE of Ravne Fault where it crosses Tolminka Springs Valley. Fault core breccia forms eroded out trough. Andrej Gosar in foreground for scale.

b) Inner Ravne Fault core at SE end of Planina na Polju within Krn Mountain area showing highly fractured exposures and steep NE dipping fault surfaces.

c) Sub-horizontal fault mullions at SE end of Planina na Polju within Krn Mountain area indicating strike-slip sense of displacement.

d) View NW of Ravne Fault zone at NW end of Tolminka Springs Valley. PDZ: Principal Displacement Zone.

e) NE-dipping Ravne Fault plane (118º, 71ºNE), SE Planina na Polju within Krn Mountain area.

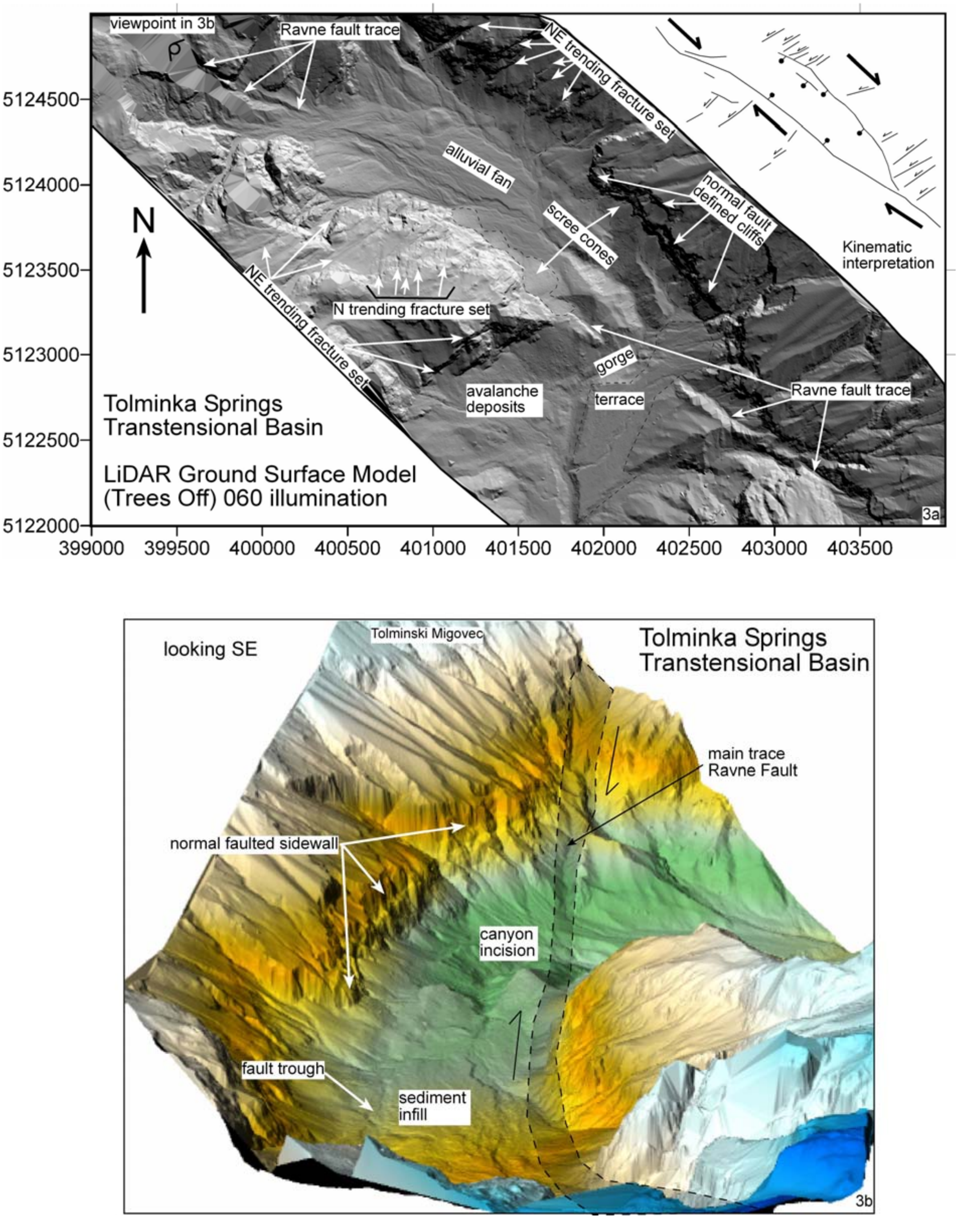


**Fig. 3**

a) LiDAR image of Tolminka Springs Valley along the Ravne Fault, NW Slovenia. Image is ground surface model (trees removed) illuminated from 060. Interpreted faults, major fractures and surficial deposits are shown. Transtensional fault array kinematic interpretation is also indicated.

b) Three-dimensional topographic perspective of Tolminka Springs Basin derived from LiDAR ground model. Main trace of Ravne Fault is indicated. Perspective is from NW looking SE; viewpoint indicated in Fig. 3a.