Introduction and approach. Fan-shaped deposits are common in formerly glaciated mountains, especially where steep tributary valleys join broad troughs; this being a classic locus where high volumes of mobilized sediment suffer a sudden loss of transport power. The term ‘alluvial fan’ generally includes both fluvial and debris-flow-dominated deposits. A group of exceptionally large alluvial fans occurs in Val Venosta, a major glacial trough in the east-central Alps, Italy. The Val Venosta group is the largest group in the Alps; concentrated glacial erosion in conducive geology among the probable cause explaining anomalous fans number and size. In this work, our attention is focused on the “Allitz/Laas” fan; it is one of the largest symmetrical fans in the Alps: it deflects the Adige River to the opposite slope foot and dominates Val Venosta as an extraordinary half-barrier. We have acquired and processed an ~4 km long high-resolution seismic reflection profile across the Allitz/Laas fan, crossing the residential area of the village of Laas. The target of this work is the study of the shallow portion (about 500 m deep) of this alluvial fan. We had two principal investigation aims. First aim is the imaging of the bedrock, in order to define its depth and consequently to estimate the thickness of sediment accumulation, as well as to analyze the morphology of the bedrock and the valley engraving. Second investigation aim is the analysis of the sediment’s stratigraphy, in order to retrace the formation history of the alluvial fan. This information will provide us with important knowledge about the debated genesis of Adige Valley. Seismic stratigraphic
analysis on seismic sections will also provide information about the interaction between the sedimentation rate and the glacier evolution.

Alluvial fan environments, often present significant challenges for high-resolution seismic exploration. The main factors hindering seismic imaging are: 1) strong lateral velocity contrasts in heterogeneous sediments of the shallow portion of subsurface; 2) unfavorable topographic conditions along the profile and 3) presence of dipping reflectors representing the bedrock. A dense wide-aperture acquisition geometry, allowing nonstandard processing and a meaningful interaction and comparison between refraction and reflection data has been proven capable of overcome most of the above-mentioned limiting factors (Improta and Bruno, 2007; Bruno et al., 2010, 2011, 2012). A dense wide-aperture acquisition geometry differs from typical common-midpoint small aperture reflection because it allows recording both multi-fold reflection data spanning a large range of offsets (from small-offset near-vertical reflections to large-offset large amplitude post-critical reflections) and deep penetrating refracted waves, which are suitable for first-arrival travel-time tomography. Tomography not only contributes information about the subsurface structure but also provides a good control on the near-surface velocity structure that is crucial for improving the quality of static corrections and, ultimately, the stacking of shallow reflections.

Local setting. Val Venosta is a major glacial trough of the east-central Italian Alps. Its lower part trends west-east for 42 km, decreasing its main altitude from 900 to 500 m above sea level moving toward East end above Meran and it is obstructed by a large fan complex into the Adige gorge. At its West end, the Upper Val Venosta ascends north into the lowest gap in the main Alpine divide west of Brenner, the Reschen Pass (1500 m). The terrain character falls into three elevation ranges, reflecting Quaternary glacial impact over an orogenic landscape that had become generally ‘mature’ and well adjusted to late Tertiary base levels. Below 2400 m altitude, steep slopes fall to the Venosta glacial trough, without high rock-walls; tributary valleys are more V-shaped than U-shaped because of gravitational and fluvial overprinting. The geology is predominantly represented by Austro-Alpine metamorphic units (Agliardi et al., 2009b), comprising metapelites and metapsammites, with subordinate orthogneiss, metabasites and calc-schists. slices of sedimentary Upper Palaeozoic-Mesozoic cover occur around the Upper Val Venosta. The entire stack is cut by north, east-, NE- and SW-trending fractures, strongly constraining the drainage pattern and the strength of rock masses. (Jarman et al., 2011) The valley bottom hosts the biggest group of anomalously large fans within the European Alps, the origin of which is still matter of debate. If on one hand Jarman et al. (2011) hypothesize a catastrophic formation of the fans modulated by large, rapid slope failures, on the other hand, a mechanism of paraglacial progradation, mainly mediated by debris flows, represents the alternate theory. The latter interpretation would be sustained by the high contemporary rates of debris-flow transport recorded in basins covered by glacial and glacio-fluvial deposits across the entire AltoAdige/Sudtirol region (Brardinoni et al., 2012).

Data acquisition and processing. We acquired four seismic profiles, with a total profile length of ~4 km. Three profiles (Lasa_1, Lasa_2, Lasa_3) are longitudinal to the valley, and one profile (Lasa_4) cuts the alluvial fan as a transverse section, crossing profile Lasa_1 (Fig. 1). The logistic of line acquisition was very hard on profiles Lasa_2 and Lasa_3, because these profiles come across the residential area of the village of Laas. P-wave seismic reflection data were collected using a single 6382-kg IVI-Minivib® truck. At each vibration point we stacked 2, 15 s long, 10–200 Hz sweeps generating a 1s correlated record with 1ms sample interval. Source move-up was 5 m. Single 10-Hz vertical geophones were also placed at 5 m intervals. Tight spacing of both geophone and vibration points ensured a very regular and dense subsurface coverage, with common midpoints spaced of only 2.5 m. The acquisition parameters were expressly designed to keep maximum data redundancy.

The identification of the optimal processing sequence depends on the quality and characteristics of the data recorded. The reflection processing was performed through Landmark
commercial software ProMAX. The data processing consisted of three main phases: 1) pre-processing, 2) velocity analysis and stacking; 3) post-stack migration. First operation was the cross-correlation between the wave function generated by the source (sweep) with the seismic array seismograms. Subsequently, we assigned to all traces a geometry in UTM WGS84 coordinates. The profiles were acquired and therefore processed with a crooked line geometry. A minimum phase filter was estimated by the source sweeps. The main and longer part of refraction processing was the picking of the first arrivals. The reading of the first arrival phases was performed on the entire dataset, consisting of about 110,500 traces. The first arrivals were
checked for consistency using the reciprocity rules of Ackermann et al. (1986) and then inverted using a commercial software, that is part of the SeisImager® package, distributed by Oyo Corporation Ltd. and based on the work of Hayashi and Takahashi (2001). The tomographic models, not only provide important information for interpretation of the seismic profiles, but are also used in the reflection processing sequence, integrating the semblance-based velocity models used for the normal moveout correction. First break picks were also used to apply refraction static corrections (Taner et al., 1998). The preliminary velocity models were obtained by picking the maximum of semblance (Neidell and Taner, 1971). The preliminary velocity models and the resulting stacks were refined by two cycles of residual static corrections and velocity analysis (Clerabout and Ronen, 1985). The final stack sections were processed with a spatial filtering algorithm, and depth migrated using a Kirchhoff post-stack depth migration.

**Discussion and conclusions.** The data acquired in Laas (BZ) are characterized by good signal-to-noise ratio. The use of a “dense wide aperture” geometry, allowed us to sample reflected and refracted phases in a wide offset range, therefore reaching a comparable depth penetration for both reflected and refracted phases. Combination of seismic reflection and first-arrival tomography provided overlapping and matching information in terms of reflectivity models and P-wave tomographic velocity models along our profiles, and allowing us to imaging from the topographic surface down to the top of the basement. All tomographic models show heterogeneous P wave velocities and strong gradients: P-wave velocities vary from a minimum of about 0.5 km/s at the surface and increase up to over 4.5 km/s at top of the metamorphic bedrock. The comparison between tomographic models and depth migrated sections, emphasize a perfect agreement between the trend and the geometry of seismic-stratigraphic units on the migrated sections with the P-wave velocity models from the first-arrival tomography.

The migrated profile “Lasa_1” shows a very shallow reflector with high amplitude at an average depth of 150-200 m (Fig. 2). Its amplitude characteristics and the high stacking velocity associated with this reflector (\(V_{RMS} > 3500\) m/s), suggest that this event is generated by the reflection from the top of metamorphic bedrock. This interpretation is supported by the agreement between the reflection event and the high velocity (\(V_p > 4\) km/s) of seismic tommography.

The migrated profiles of Lasa2_3 (Fig. 2) clearly image the structure of the valley and the trend of the top of the metamorphic bedrock below. The profiles also show an a sub-horizontal
reflective series, probably related to the Adige River fluvial deposits which fill the more depressed portion of the valley, where at present there is the Adige River bed. The thickness of this sub-horizontal reflective series is about 100 m. Below CDP 25 the bedrock undergoes a sudden increase in dip towards the south and its apparent depth becomes ~200 m below CDP 150. From this point forward, the bedrock top is no longer visible on the seismic section, and reappears below CDP 350 at about the same depth of (i.e. ~150 m from surface) with an opposite dip, therefore decreasing its depth (~40-50 m) towards the end of the profile. Seismic tomography velocity information is perfect agreement with seismic reflection data. The contour line 4 km/s (interpreted as indicative of the bedrock top) shows indeed a clear and distinct trend to deepen rapidly towards the central part of the profile, with a maximum depth of more than 200m, between metric progresses 600-1150 m, below the surface location of Adige River (Fig.2). Between CDPs 0-250 and CDPs 325-479, the fluvial deposits, are covered by an area of poor reflectivity, similar to those present in the upper part of profiles “Lasa_1” and “Lasa_4”. Based also on the P-wave velocity form tomographic models these seismic facies can probably be associated with dry, nonreflective alluvial fan deposits (Fig. 2).

Along tomographic profile “Lasa_4”, ray penetration is lower (on average between 50 and 100 m) because the basement is shallower than on the other profiles. Lasa_4 profile also shows the maximum vertical gradients of velocity, certainly caused by a shallow bedrock (with the top at about 50 m from surface) that tends to deepen toward the east. These features are in agreement with the reflection image, which confirms both the depth of the bedrock top, and its clear dip towards the east. This dip of the top of the basement explains a step of ~35 m in Fig 2 affecting the top of bedrock between the adjacent parts of profiles “Lasa_1” and “Lasa_2_3”. In fact, by analyzing the depth migrated and tomography profiles of “Lasa_2_3” and comparing them with those of “Lasa_1” it is evident a 35 m vertical offset of the top of the bedrock. This vertical offset is well justified by the lateral offset (about 300 m) between the two profiles (see Fig. 1), and by the slope towards the east of the bedrock top on “Lasa_4” migrated profile.

References


