

## SEISMIC RESEARCHES ON LANDSLIDES IN WALLACHIAN SUBCARPATHIANS\*

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*Recherches sismiques dans les zones avec des glissements de terrain des Sous-Carpates de Munténie.* Dans les zones Ulmetu – Pucioasa, Telega – Câmpina et Slănic-Prahova de l'aire des Sous-Carpates de Munténie ont été réalisées des applications de la sismique de réfraction, dans la variante de la technologie d'acquisition des données de détail.

Dans le premier périmètre, les résultats sismiques ont permis l'élaboration d'un modèle de la dynamique du terrain sur un alignement représentatif, tout en mettant en évidence un secteur de préservation naturelle du versant à long terme (proche de la cote maximale du relief local), un segment caractérisé par un coefficient de sécurité au glissement réduit (pour la raideur située immédiatement en aval de la face principale de décrochage) et, par la suite, une zone étendue avec une dynamique d'écoulement active, favorisée par l'effondrement conséquent du soubassement. Dans les autres aires, les mesures sismiques ont permis la construction d'esquisses avec des isohypses pour les interfaces lithologiques ou de séparation des volumes de rochers altérés, et aussi des représentations avec des valeurs isopaques. La morphologie du principal niveau analysé, représenté par la surface de glissement, et des distributions des vitesses sismiques a permis de faire des précis sur la formation et l'évolution de la dynamique des versants.

L'ensemble des données sismiques a démontré le potentiel de cette méthode géophysique d'assister la cartographie géotechnique par la reconstitution véridique de la section de petite profondeur et la différenciation du compacteur des dépôts constituants, avec des prolongements efficaces dans des évaluations géotechniques des zones avec des glissements de terrain.

*Key words:* shallow seismic refraction, landslides, geotechnical parameters, contour and isopach maps, Subcarpathians, Wallachia.

### INTRODUCTION

The analysis of natural hazards involved by landslides requires the revealing of both the depth and relief of the slipping surface, and also to precise the extension of the dislocated material areas.

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The evaluation imposes detailed geophysical investigations, and among them the seismic exploration is necessary due to both continuous and quantitative information along the survey lines. With these peculiarities some measurements have been performed inside Ulmetu – Pucioasa, Telega – Câmpina and Slănic-Prahova perimeters, belonging to the southern hilled zone of Bend Subcarpathians (Fig. 1).

After introducing the main aspects of the seismic data acquisition technology, the significant results of the homonymous methodology applications concerning shallow geological section in the above mentioned areas will be presented.

### SEISMIC DATA ACQUISITION

Seismic investigations were based on the refracted waves correlation method on complete observing spreads (split, end off and in-line offset impact points), with detailed character (geophone spacing of 1.5, 2 or 3 m, and shot point distance intervals of 20–69 m). The elastic waves have been generated by 10 kg weight dropping on the ground. The field equipment used was one 24 channels portable analog instrument, ABEM TRIO SX type, upgraded with a PC having an in real-time data acquisition and stacking system.

The seismic lines arrangement was designed in accordance with the geomorphologic features, as preferred direction being the structural axis of the landslide and complementary quasi-orthogonal directions as well as across the main head scarp (Figs. 1, 3).

The direct and reverse traveltimes curves were obtained on spreads with length between 46 – 138 m.

The recorded seismic waves consisted of the direct signal traveling through alluvial deposits with 200–400 m/s velocities denoting some loose deposits, and the refracted waves generated at intermediate and bedrock levels with velocities up to 2600 m/s.

Seismic sections have been obtained using the plus/minus Hagedoorn method, for the forward and reverse shots (Rockwell, 1970), and delay time procedure, for the uncompleted branches of the traveltimes curves (Barry, 1970).

### ULMETU – PUCIOASA AREA

Seismic investigations have provided information concerning the boundaries of the slipped material, as well as some evaluations of the ground dynamics in the experiment area.

Three seismic lines whose results are reported on the synthetic alignment A–B were performed (Fig. 2). The main geolastic boundary with the greatest seismic

velocity contrast is attributed to the interface between Quaternary alluvium and Oligocene deposits which is considered as a general slipping surface.

Below, information are structured in two sections, in connection with specific targets.

#### STAGE OF LOCAL LANDSLIDE

Along the line *Pr. 1* (Fig. 3), the refraction boundary is alternatively quasi-horizontal and monoclinal (about 10° tilt) and it is situated at average depths from 2 to 4 m, except a restricted space (50–80 m) where the overlaying deposits reach up to 5 m thickness. These quasi-horizontal segments are “steps” which reduce the gravitational tangential component – T (Florea, 1979) at the slipping plane.

The boundary velocities ( $V_L$ ) are approximately constant, about 1800 m/s, except the 110–140 m distance interval where  $V_L = 1400$  m/s, caused probably by a much more altered bedrock or some local lithological variations, and  $V_L = 2100$  m/s at the NE end of the *Pr. 1* line (360–390 m distance).

The last value was obtained further on the profiles *Pr. 2* and *Pr. 3* situated successively on a higher topography towards the Miercani hill top.

The mark that differentiated the main two velocity ranges (1800 m/s, respectively 2100 m/s, Fig. 3) was interpreted as the contact between the two Oligocene facies: Pucioasa layers (shale deposits) and Fusaru sandstone (Fig. 2), limit indicated by geological mapping (1:50 000 scale) at about 25 m SW of the mentioned point.

Thus the seismic investigation offers shallow structural data regarding the landslide process and in addition may accurately delimit, inside perimeter, the boundary between above mentioned Oligocene facies by seismic velocity mapping.

#### LANDSLIDE PREDICTED EVOLUTION

The quantitative data regarding the physic-geological local characteristics, such as thickness and homogeneity of formations, as well as topography of seismic-geological boundaries, allows a few considerations about the dynamic potential of the landslides.

Thus the traveltime curve on the *Pr. 2* line (Fig. 4, top image), placed close, lower the uppermost face scarp (Fig. 2), allows to construct the correspondent cross-section (Fig. 4, middle part).

The model highlights the representative contrast of seismic waves velocities, 200–500 m/s vs. 2100 m/s, considered to define the slipping interface. This was the support-section used to evaluate the slope stability potential.

According to the Maslov-Berer method (Florea, 1979), the section was divided in seven strips representing some active and passive prisms and the

following values for mechanical parameters were accepted:  $20^{\circ}$  internal friction angle ( $\phi$ ),  $0.1 \text{ daN/cm}^2$  cohesion ( $c$ ) and  $1.7 \text{ tf/m}^3$  specific gravity ( $\gamma$ ).

The obtained safety factor value,  $\eta = 1.16$  (Fig. 4, lower part) denotes a relative poor stability and suggests a possible local reactivating of the landslide.

Further on, upward to the Miercani hill top, the seismic line *Pr. 3* was performed (Fig. 3). The traveltime curves highlight progressive increase of seismic wave velocities (up to  $1300 \text{ m/s}$ ), due to some interbedded of gravels, clays and sands (of Quaternary age, according to the geological mapping data) and it allows to construct the surface of the Fusaru sandstone, disposed generally quasi-horizontal.

Finally, the conclusion based on seismic information sustains the stability prediction of the Miercani hill top zone, the process of ground slipping being favored downstream by thin and poorly compacted alluvial deposits, as well as by the relative large tilt of the bedrock (Fig. 3).

#### TELEGA LANDSLIDE PERIMETER (NE OF CÂMPINA TOWN)

The landslide area is situated on the left bank of homonymous river (Fig. 5). The specific features: large fissures on both longitudinal ( $120 \text{ m}$  long,  $0.3\text{--}0.5 \text{ m}$  width) and transversal ( $48 \text{ m}$  long,  $0.3 \text{ m}$  width) directions, zig-zag fissures (around  $65 \text{ m}$  long,  $0.5 \text{ m}$  width), slide valleys, pronounced slide waves, pastures and mudflow sectors are extended over  $2 \text{ sqkm}$  surface. Slide masses constituted by loose quaternary materials, disturbed by this peculiar microrelief, and Miocene coarse fragments composed by altered sandy-clay and marly-clay formations are reposed on the compact Miocene complex. Inside of the last deposit, salt lenses have been identified by the geological mapping.

The seismic investigation main objective was to evaluate the thickness range of the landslide body. Consequently, specific records have been performed over set lines, composed by one longitudinal alignment in respect to the principal direction of the landslide, and another four quasi-transversal profiles (Fig. 5).

Traveltime curves (Fig. 6a) displays besides the direct impulse –  $t_{dir}$ , other two signals: the head-refracted waves  $t_1$  and  $t_2$  that propagate the first along the Miocene weathering top and the other at the relatively compact Miocene formation surface. The latest marker was considered to represent the bedrock, the level that reacts as the major slide plain.

Cross-seismic section reveals (Fig. 6b) a larger development of dislocated land in the middle part of NW half of the line *Pr L* (approximately between  $20\text{--}69 \text{ m}$  marks). Additionally, based on the various boundary velocity values, a higher action of exogenous processes on the bedrock in the elevated sector of the same seismic line can be supposed (between  $140\text{--}220 \text{ m}$  pickets).

Congruent information was collected on the transversal lines. The exemplified seismic section (*Pr T1*, Fig. 7) illustrates two relevant elements: the

unstable deposit having the greatest thickness (over the distance interval 90–105 m), showed previously on the longitudinal line, and the largest seismic velocities for the deepest marker (3600–3700 m/s), values associated with the potential presence of salt lens caprock.

Morphological seismic results are integrated in the contour map concerning bedrock level and isopach sketch, which is referred to the overlying deposits, namely dislocated materials.

The bedrock contour (Fig. 8) reveals a quasi-monoclinial plan on which a relatively important depression is inserted, oriented SE–NW predominantly along *Pr. L* line. In the NW quarter of the map, this “negative” shape of the bedrock is redressed by a relatively plate sector that acts like a passive prism against the sliding tendency.

The isopach image (Fig. 9) reflects low values (2–3 m) in the NE extreme part, medium (9–17 m) in southern and eastern zones, and greatest thickness (up to 21 m) in the NW– central sector. The last area coincides with the gentle tilted slide plane, signalized previously, and may be interpreted as a potential mobile zone, triggered when the value of the gravity force-*G* (Florea, 1979) of the material gradual accumulation will be exceeded by the reacting tension (*T*), controlled mainly by the bedrock slope.

#### PLAIUL SLĂNIC LANDSLIDE ACREAGE

The sector is situated in the SW vicinity of the Slănic-Prahova town – an area with shallow old salt mines.

The seismic investigation of the lowest deep geological formations was focused on revealing both its thickness and boundaries in order to evaluate relevant characteristics in connection with the disrupted lands.

Data were acquired on three cross seismic lines, one of them being placed on the longitudinal direction, comparative with the main slide axis, and having its initial part on stabile zone (Fig. 10). The seismic line group was designed to a quasi-homogene coverage of the local landslide.

The essential seismic-geological features of the area are exemplified on the line *Pr. L*. The travel time-distance curve (Fig. 11a) illustrates the presence of the direct wave ( $t_{dir}$ ), which travels superficial deposits, and the refracted signals ( $t_{1-3}$ ) that denote the head waves propagating at the top of Miocene formations (altered and subsequent rocks of the same compact deposits), respectively along the Badenian accumulation surface (gyps-rock).

Corresponding cross-section (Fig. 11b) reveals both the boundaries and thickness of shallow layers, and based on velocity values it allows to characterize the degrees of the rock consolidation.

The seismic result integration is materialized in the contour maps for different levels – bedrock (Fig. 12a), intra-Miocene deposits (Fig. 12b) and Badenian gypsum

surface (Fig. 12c) – as well as in the isopach maps refer to the first and last levels specified above (Figs. 13a, b).

High-resolution character of the seismic data, involved by the detailed field technology and the specific processing methods, allow picking the resulted elevation and hypsometrical lines at 1 m interval.

The illustrations permit the following evaluations:

a) larger velocity values for bedrock ( $V_L = 1750$  m/s), combined with moderate dips of Quaternary base and intra-Miocene limit, may explain the land relative preservation in southern sector (Fig. 11);

b) the slope instability in the northern acreage is controlled by larger tilts of both bedrock (Fig. 12a) and intra-Miocene level (Fig. 12b), associated with the biggest thickness of accentuated ground displacements, up to 4,5 m (Fig. 13a);

c) the possible extension of the landslide effect up to gypsum rock level is presumed by descendent tendency marked on the contour map at the Badenian surface (Fig. 12c), in connection with the larger thickness of the overburden reposed on this level (Fig. 13b), in the NE part of the perimeter.

## CONCLUSIONS

The results of the seismic survey have shown the method capabilities to provide an accurate image of shallow depth section, with the possibility to precise the consolidation state of both shallow material and its bedrock (by means of the seismic velocity ranges).

Derived information can offer:

– reliable explanations concerning favorable conditions of the landslide development (both depressional shape and tilt of the bedrock) and also the potential elements to react sliding process (the altered stage of some compartments, as well as the zones capable of gradual accumulation of sliding materials);

– assurances regarding the slope long-term stability, prognosis based on gentle dips of litho-stratigraphic limits expressed on shallow seismic section.

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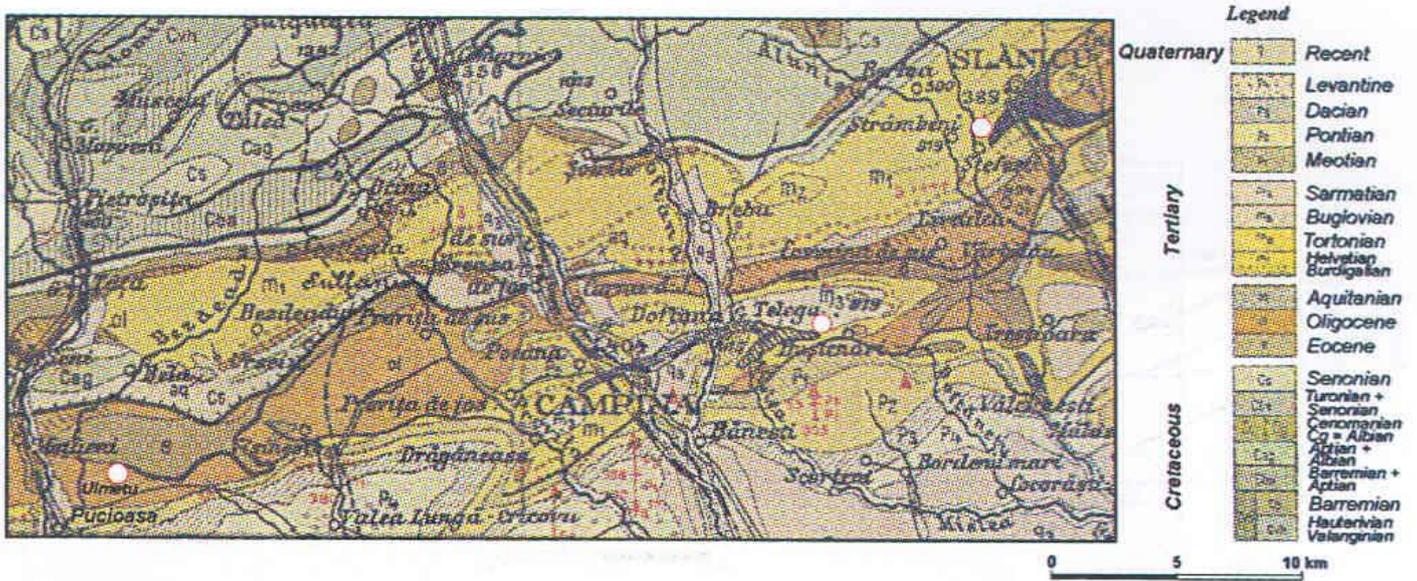
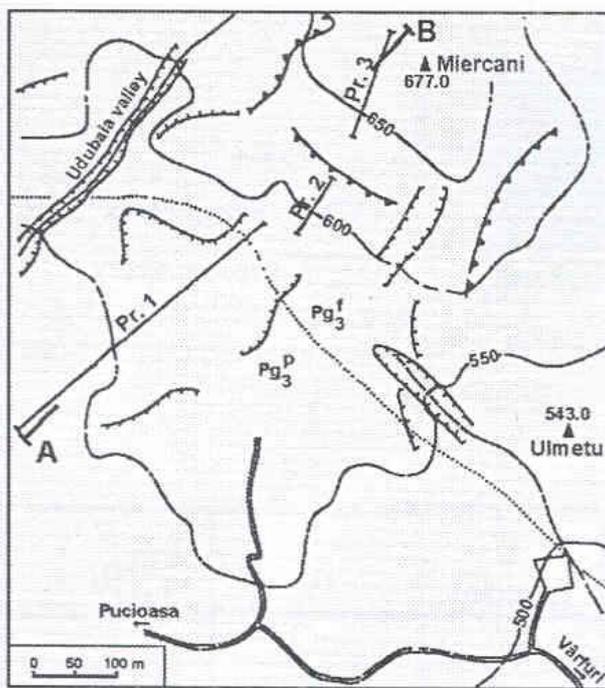


Fig. 1 – Geological map (Mrazec and Macovei, 1959) excerpt and locations of the landslide perimeters (white dots) surveyed by seismic refraction method, in Valachia Subcarpathians.



**Legend**

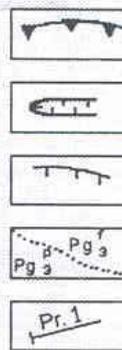


Fig. 2 – Simplified topographic and geological map of the Ulmetu landslide area. 1, Segment of main head scarp; 2, U shape trench; 3, scar of slide; 4, lithological boundary between Oligocene formations: Fusaru sandstone and Pucioasa layers; 5, shallow seismic line.

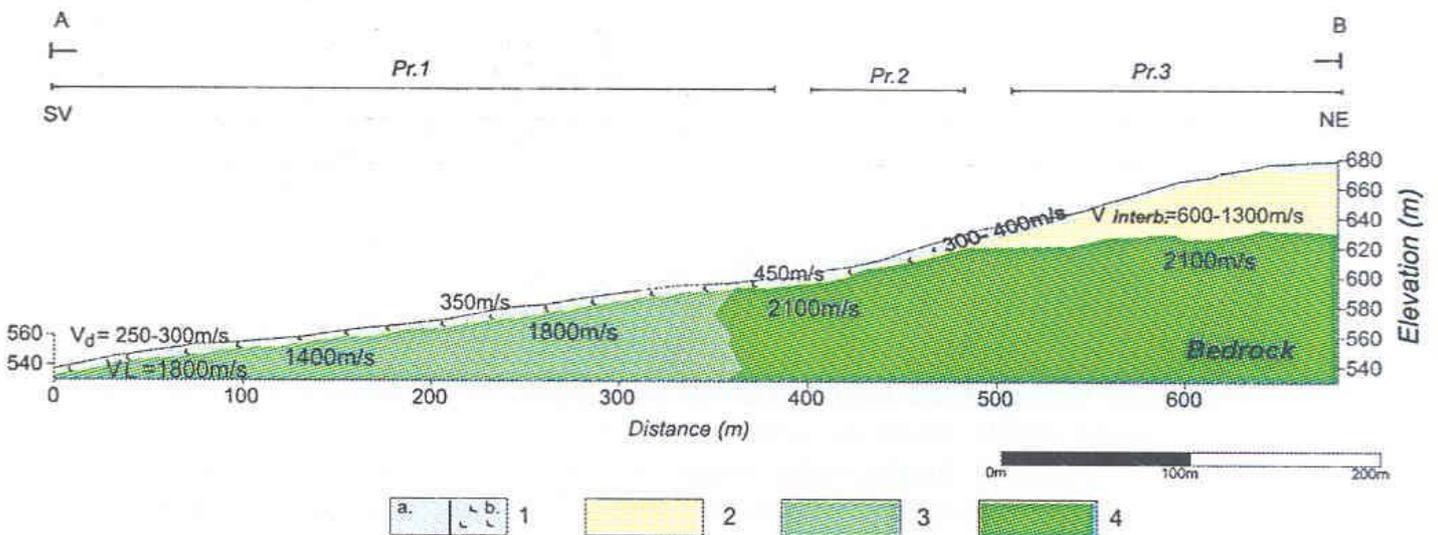
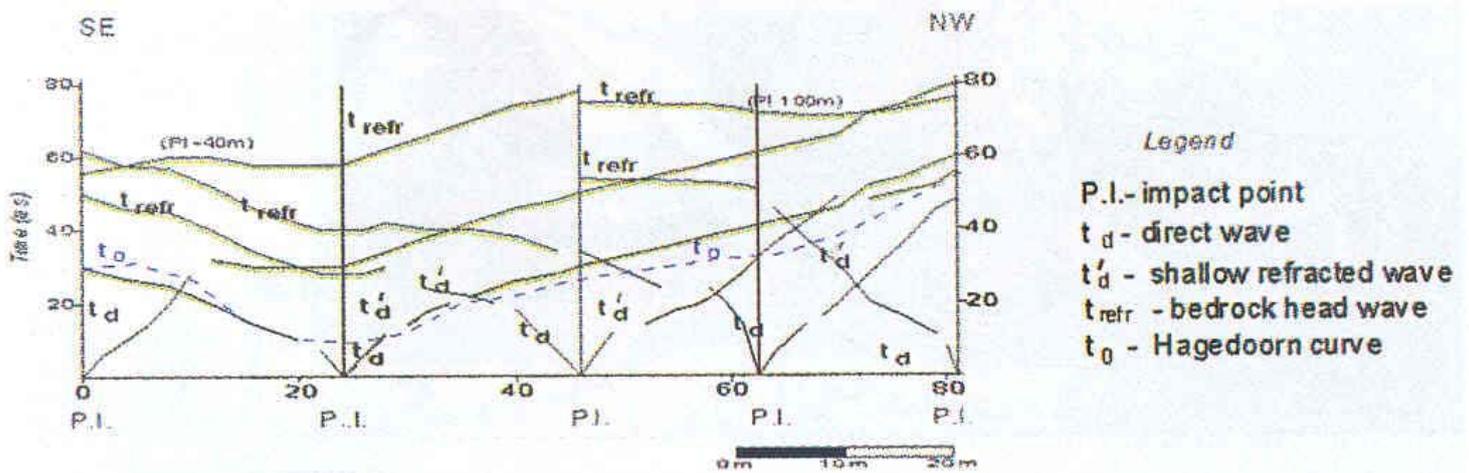
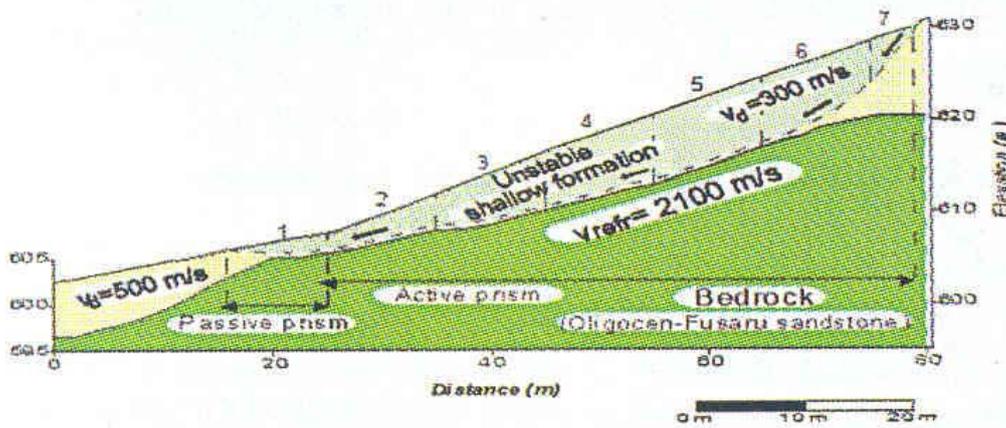


Fig. 3 – Synthetic shallow cross-section in the Ulmetu landslide area, detailed by means of the seismic data. 1, Loose Quaternary materials: a, stable; b, fissured and displaced; 2, relative compact Quaternary formations; Oligocene facies: 3, Pucioasa layers; 4, Fusaru sandstone.



Legend

- P.I.- impact point
- $t_d$  - direct wave
- $t'_d$  - shallow refracted wave
- $t_{refr}$  - bedrock head wave
- $t_0$  - Hagedoorn curve



Legend

- Sliding surface
- Seismic velocity

Prism	$h$ (m)	$b$ (m)	$G$ (t)	$\psi$ (grade)	$\varphi$ (grade)	$T$ (t)	$R$ (t)
1	2.5	10	42	30.9	-3	-2.2	26
2	5.5	10	92.5	25.2	13	21.35	41.35
3	8	10	134	23.6	19	46.14	56.9
4	8	10	134	23.6	20	48.77	57.2
5	9	10	151	23.2	22	61	64.17
6	6	10	85	26	40	71	50
7	2	4	10	33	50	12,15	9

$$\eta = \frac{\sum R}{\sum T} = \frac{304,62}{263,2} = 1,16$$

Fig. 4 – Slope stability evaluation based on shallow seismic data of the *Pr. 2 line*. Top: Traveltime curves. Middle: correspondent seismic cross-section. Lower: physic-mechanical parameters of the composite geological section model used to determine safety coefficient by Maslov-Berer method (Florea, 1979). Symbols in the tabel:  $h$ ,  $b$  and  $G$  height, width, respectively weight of the band-prism;  $\psi$ – angle of the friction force;  $\varphi$ – angle between sliding surface and gravific force direction;  $T$  and  $R$  – tangential and resistance forces.

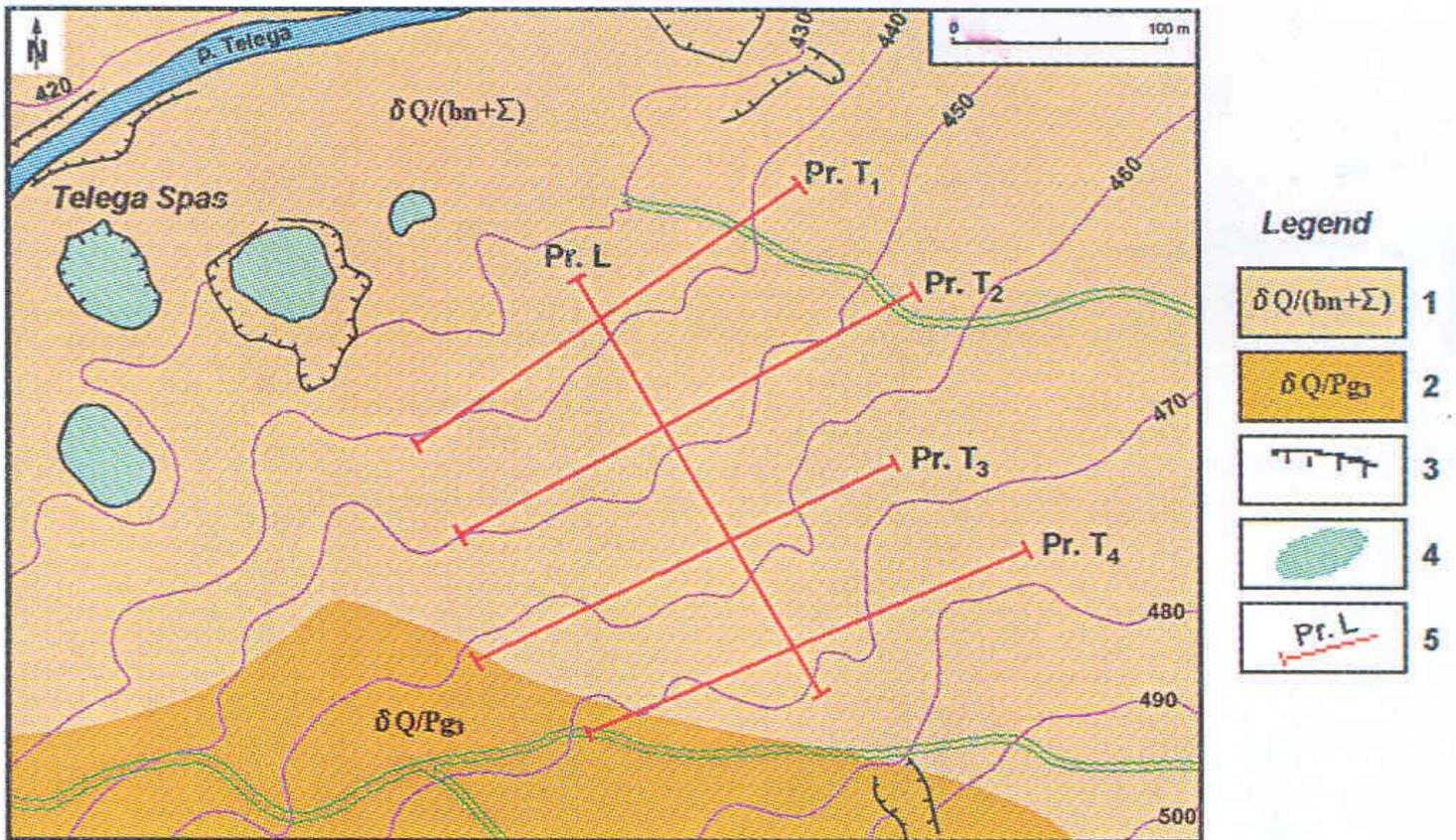


Fig. 5 – Simplified topographic and geological sketch of the *Telega landslide area*. Quaternary deposits overlying Neozoic formations: 1, Miocene; 2, Oligocene; 3, scar of the landslide with a scarp more than 5 m height; 4, salt lake formed in old mine cavities; 5, seismic refraction line.

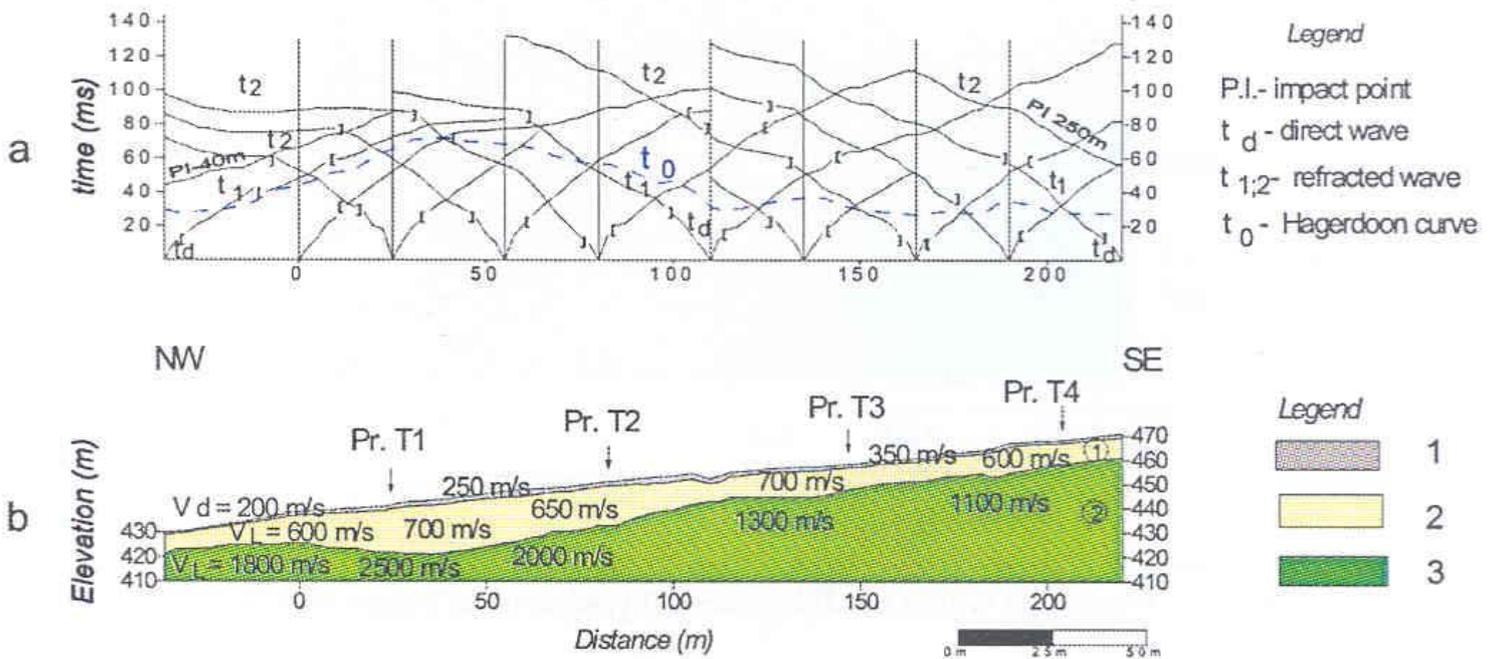


Fig. 6 – Refraction seismic line *Pr. L Telega*. a, Travel time-distance curves; b, correspondent seismic section. Slide rock masses: 1, loose Quaternary material; 2, Miocene debris; 3, Miocene bedrock.

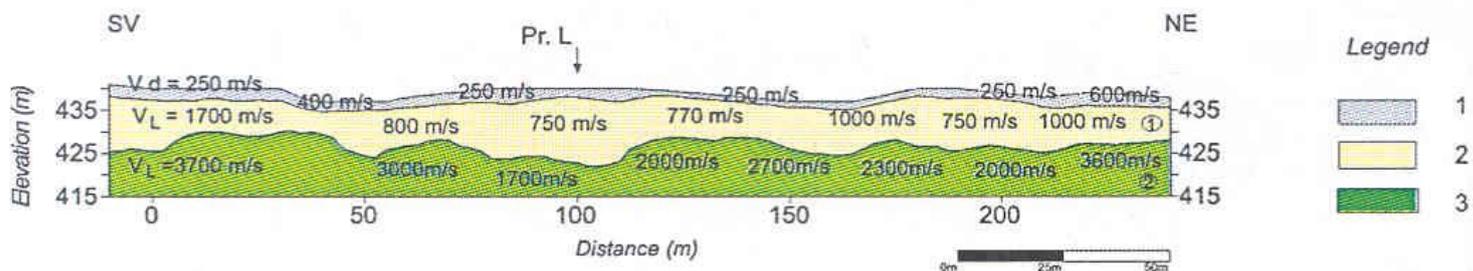


Fig. 7 – Seismic cross-section on the transversal *line Pr. T, Telega*. Slide rock masses: 1, loose Quaternary material; 2, Miocene debris; 3, Miocene bedrock.

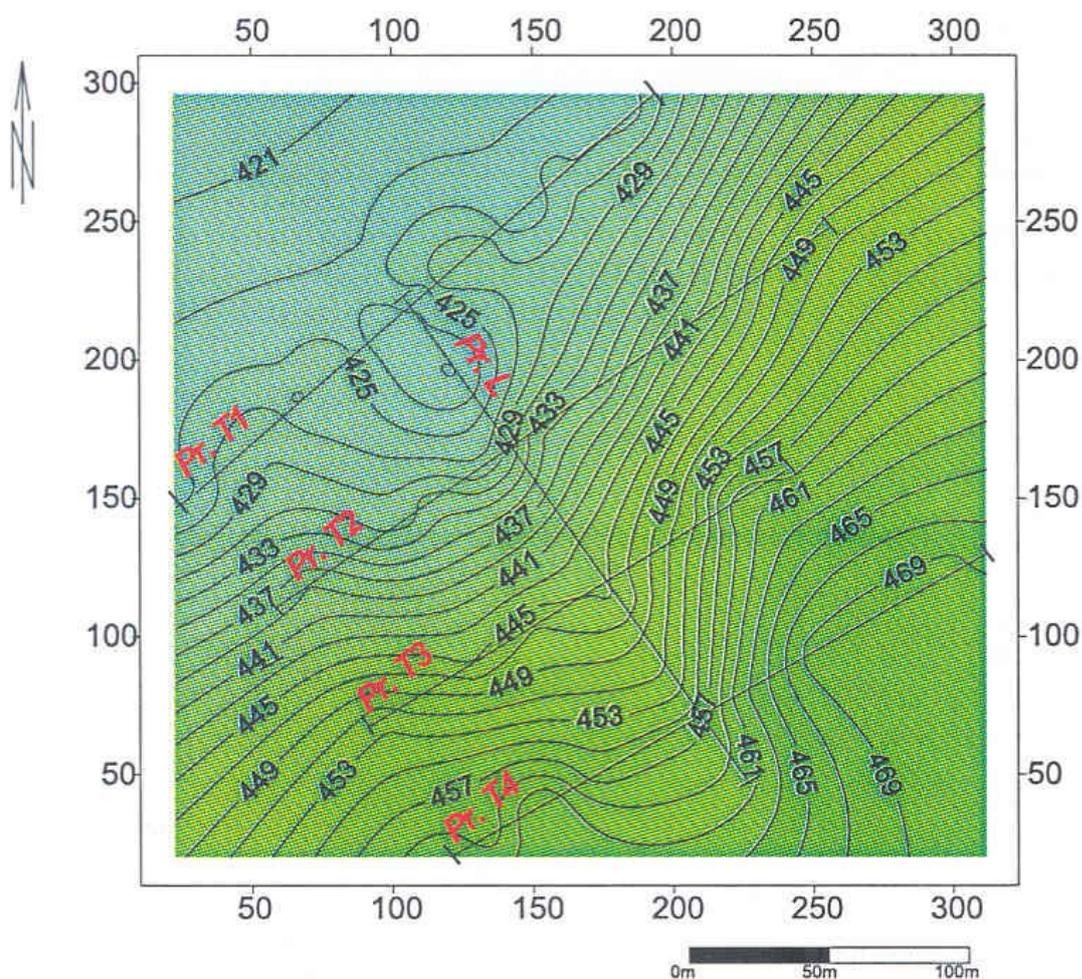


Fig. 8 – Contour map is referring to the main sliding plane represented by surface of the compact Miocene formations within *the Telega area* (hypso-metrical values in meters).

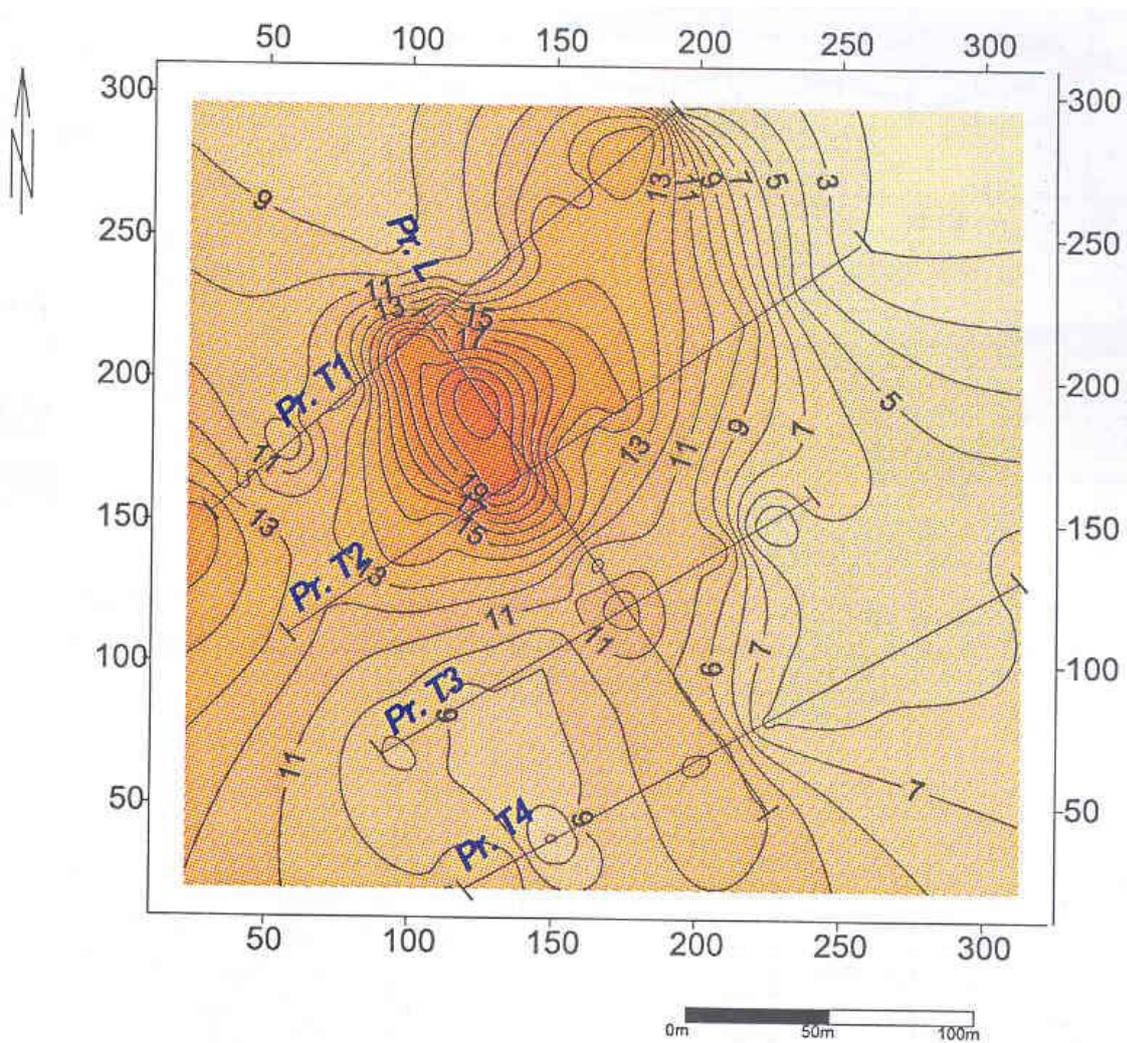


Fig. 9 – Isopach map is referring to the sliding mass ensemble for the *Telega area* (isopach values in meters).

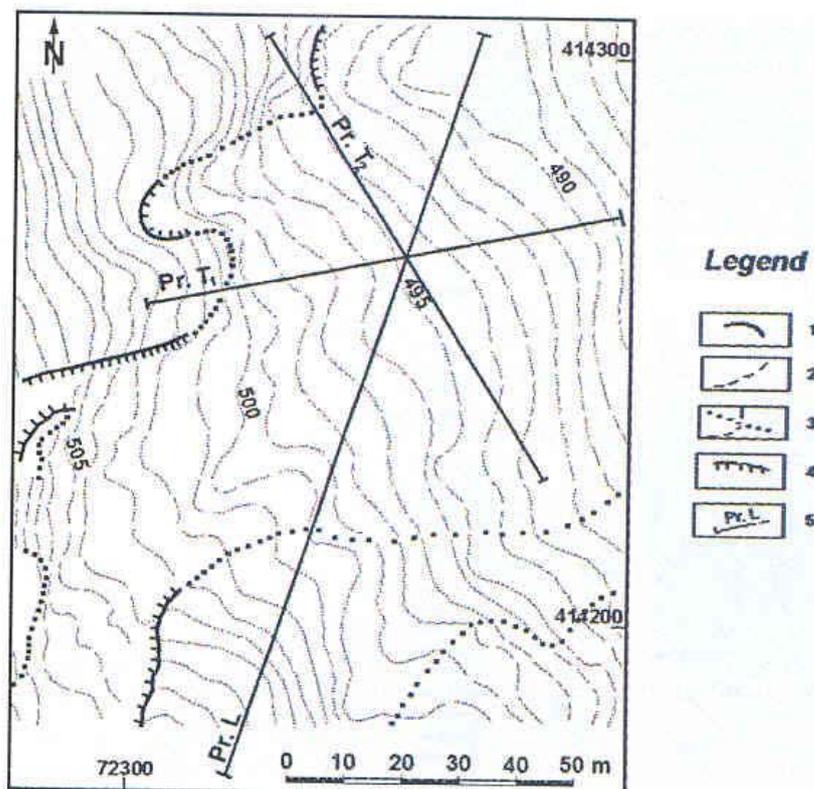


Fig. 10 – Detailed topographic sketch for the *Plaiul Slănic landslide area*. Elevation curve in: 1, stable zone; 2, creeping terrain acreage; 3, boundary soil cracks; 4, scar of old landslide with scarp more than 1 m height; 5, seismic refraction line.

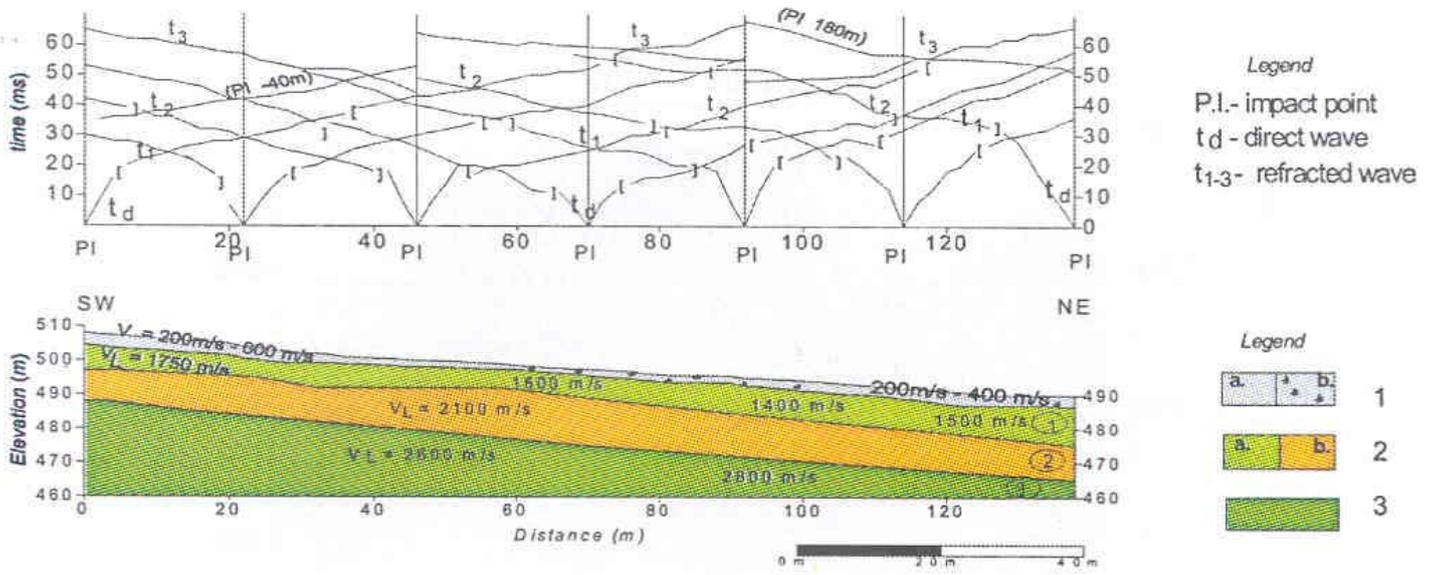


Fig. 11 – Seismic line Pr. L. Plaiul Slănic. Top: traveltime distance curves; low: seismic cross section. 1, coarse superficial deposits: a, actual stable; b, unstable; 2, Miocene formations: a, weathered zone; b, compacted rock-mass; 3, gypsum rock.

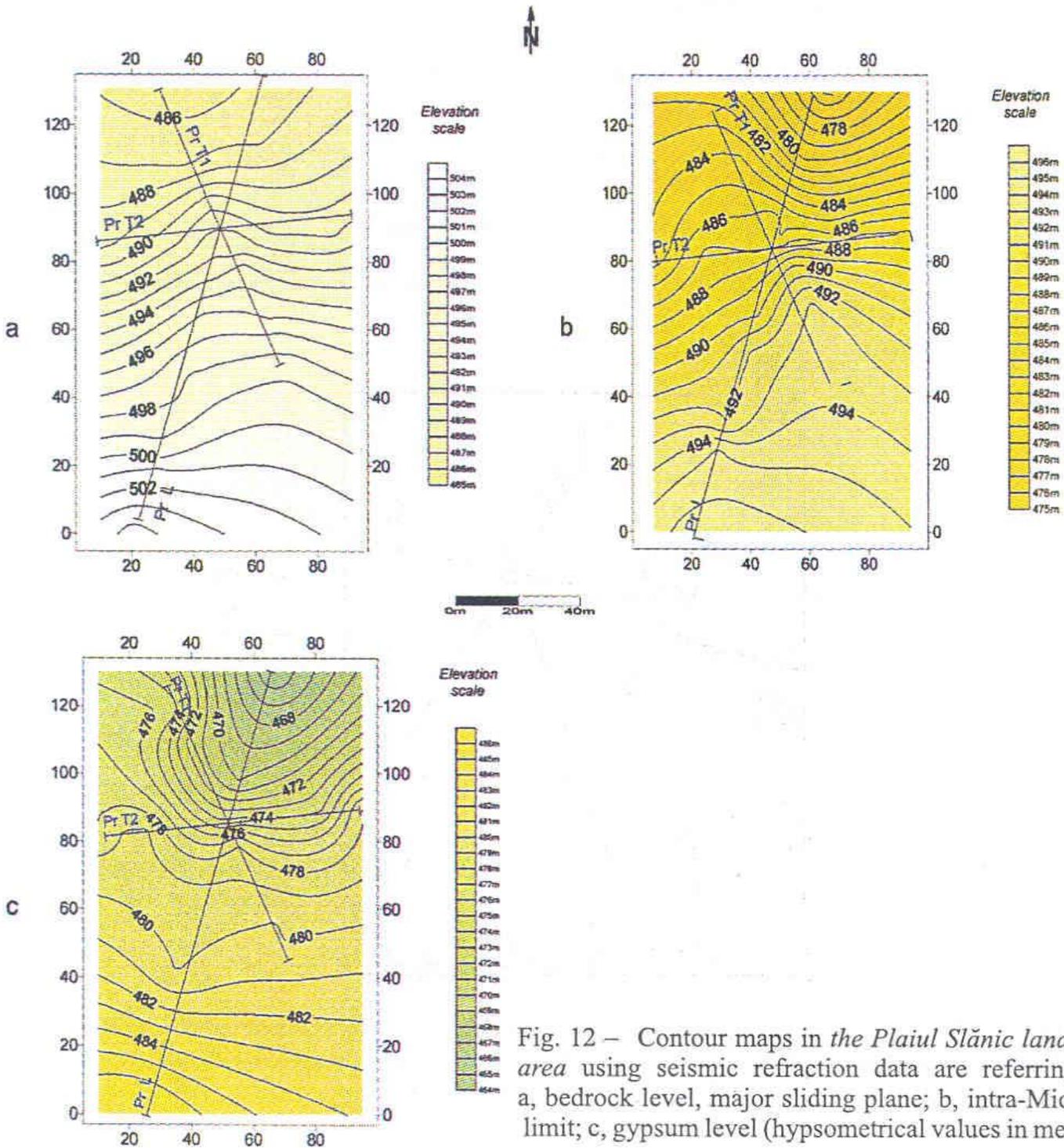


Fig. 12 – Contour maps in the Plaiul Slănic landslide area using seismic refraction data are referring to: a, bedrock level, major sliding plane; b, intra-Miocene limit; c, gypsum level (hypsometrical values in meters).

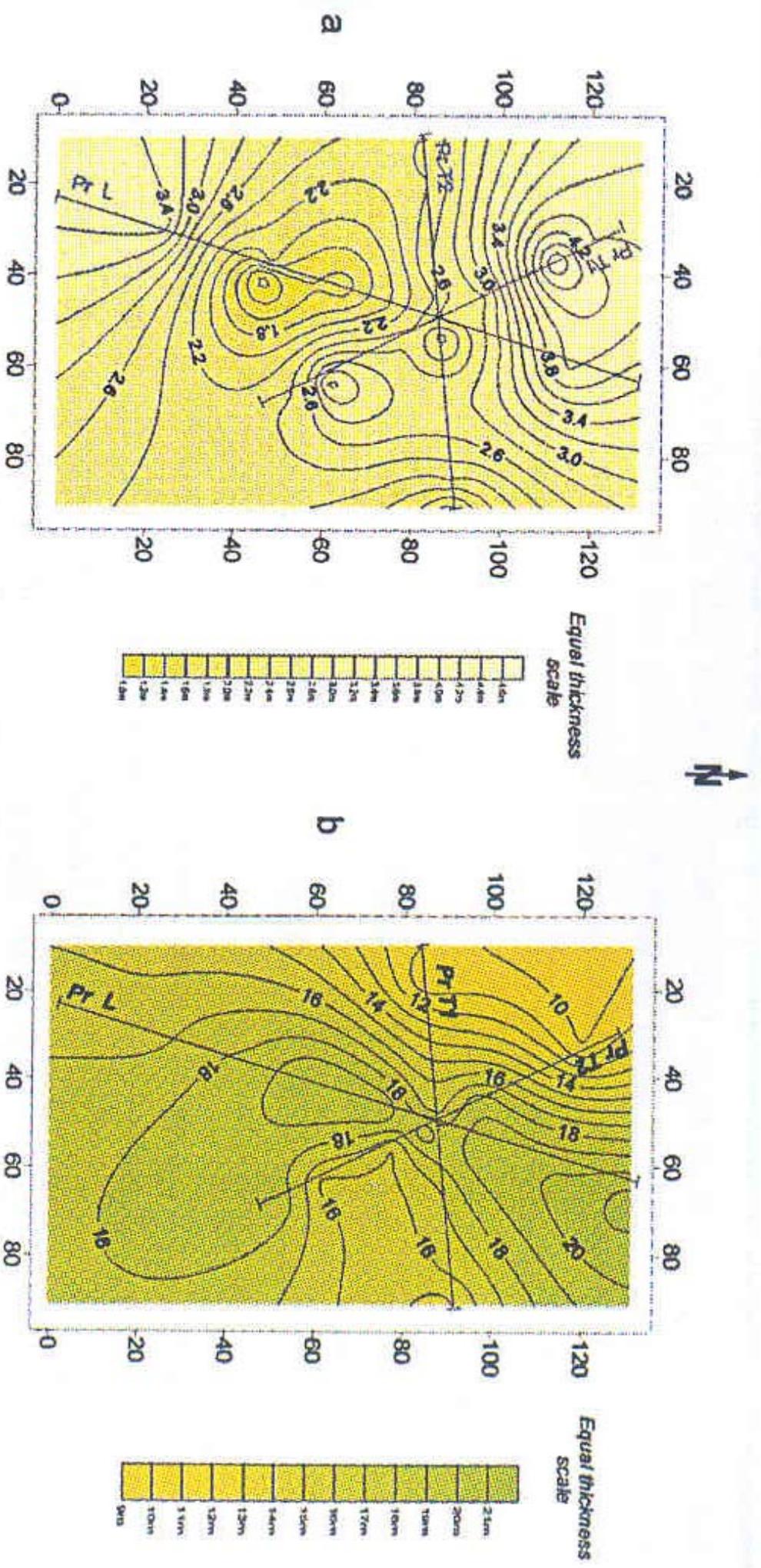


Fig. 13 – Isopach maps based on seismic refraction data, in the *Plaiul Slănic landslide area*. The images are referring to: a, principal displaced rock-mass; b, overburden masses above the gypsum level (isopach values in meters).