G. BRESSAN (*) - R. DE FRANCO (**) & G.F. GENTILE (*)

ACTIVE FAULTING AND SEISMOGENIC ASPECTS OF THE FRIULI AREA

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ABSTRACT

A 3-D P velocity model of the crust inferred from tomographic inversion, with local earthquakes recorded by the seismic array of Osservatorio Geofisico Sperimentale, is combined with geological and geophysical data to obtain a structural model of the Friuli area. A high velocity body is recognizable below 6 km depth, interpreted as a southward thrusted wedge of Paleozoic and metamorphic rocks complex, considered as basement. The thrusted sedimentary cover is detached from the basement. The comparison with seismicity suggests that the wedge represents the main seismogenic zone. The depth distribution of seismicity is related to the variation from a brittle to a ductile mode of deformation and the brittle/ductile transition lies at about 10 km depth.

RIASSUNTO

Nel presente lavoro è stato elaborato un modello tridimensionale di velocità delle onde P dell'area friulana maggiormente interessata dalla sismicità, con tecniche di inversione tomografica, a partire dai dati registrati dalla rete sismometrica dell'Osservatorio Geofisico Sperimentale. Dal confronto con dati geologici e geofisici è stato ricavato un modello strutturale dell'area interessata. L'aspetto saliente è costituito da un corpo ad alta velocità, presente a profondità superiori ai 6 km, interpretato come una scaglia sovrascorsa verso sud, costituita da un complesso di rocce sedimentarie paleozoiche e rocce metamorfiche. Tale complesso viene assunto come basamento. La copertura sedimentaria è scollata dal basamento. Il confronto con la sismicità fa ritenere che tale corpo costituisca la principale zona sismogenetica. La distribuzione in profondità della sismicità in tale settore è legata ad una transizione crostale tra dominio fragile e dominio duttile, presente ad una profondità di circa 10 km.

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KEY WORDS: Tomography, active faulting, seismogenesis, brittle-ductile transition.

PAROLE CHIAVE: Tomografia, fagliamento attivo, sismogenesi, transizione fragile-duttile.

INTRODUCTION

The present study represents a revised and updated version of a previous research of BRESSAN *et al.* (1992), with more recent and complete geophysical informations.

The combined analysis of a 3-D crustal velocity model, obtained by tomography inversion techniques (THURBER, 1981; EBERHART-PHILLIPS, 1986), and the seismicity allows the construction of structural models of the crust and the characterization of seismogenic zones. The focal depth distribution contributes to the definition of the seismogenic layers. The depth extension of seismic activity in the continental crust is related to the transition from a dominantly brittle regime involving frictional sliding to a ductile regime where shearing is accommodated by aseismic deformation (MEISSNER & STREHLAU, 1982; SIBSON, 1983).

The aim of the present work is to investigate the main seismogenic features of the Friuli area by a comparison of a crustal model, the seismicity and a brittle-ductile model of stress release.

The structure of the Friuli area is the product of superposition of Mesoalpine, Neoalpine and Plio-Quaternary tectonic phases (DOGLIONI & BOSELLINI, 1987), which caused severe shortening, mostly in the central sector (CASTELLARIN *et al.*, 1979), with a complex deformation pattern. The area consists mainly of sedimentary rocks which range from Paleozoic to Quaternary (Fig. 1). The main tectonic structures are low angle south-verging thrusts striking E-W and buried Dinaric thrusts with SW vergence. The compressive structures are intersected by transcurrent and normal faults striking about N-S, NW-SE and NNE-SSW. The tectonic contact between Paleozoic and Mesozoic deposits is marked by a dextral transcurrent fault (the Fella-Sava line) which strikes E-W. Neotectonic activity from Middle Pleistocene to Holocene Times was more intense in the central sector of the study area (ZANFERRARI *et al.*, 1982).

The P-wave velocity distribution reported by the ITALIAN EXPLOSION SEISMOLOGY GROUP & INSTITUTE OF GEOPHYSICS, ETH, Zurich (1981) supports the hypothesis of a thickening of the crust in this area. The thickness of the crust varies from 35 km under the Adriatic Sea to 50 km under the Alps. The middle crust is characterized by a low velocity zone at a depth between 10 and 20 km. High velocity values (6 km/s) are detected in the upper crust.

Historical seismicity has mainly affected the central

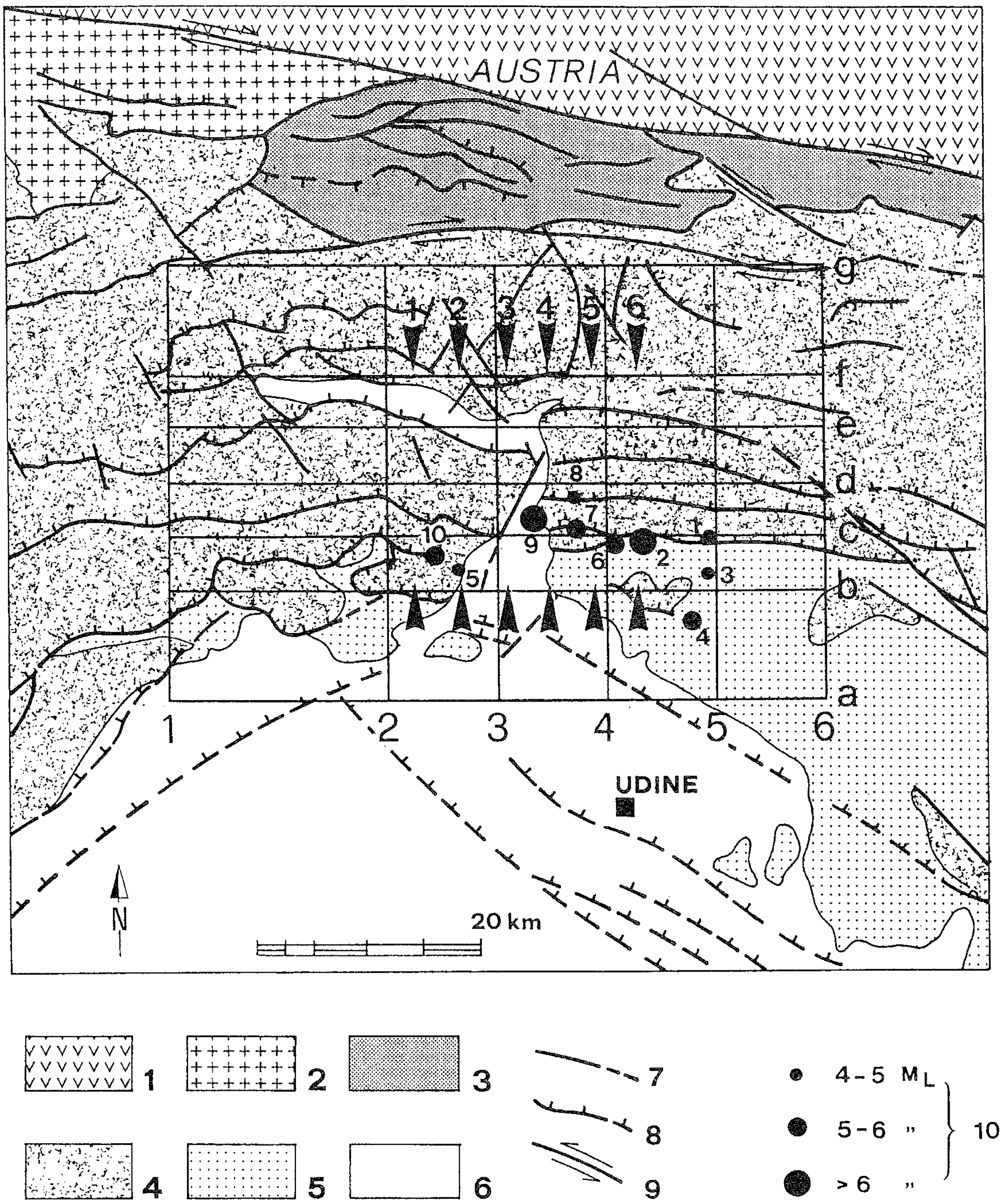

Fig. 1 - Schematic geological map of the Friuli region. The grid where the 3-D velocity model has been computed is shown. 1 = Austroalpine units: basement and sedimentary cover; 2 = methamorphic basement; 3 = Paleozoic units; 4 = Mesozoic units; 5 = Tertiary *flysch* and molasse; 6 = Quaternary deposits; 7 = fault; 8 = thrust; 9 = strike-slip fault; 10 = epicentres of the 1976-77 sequence. Arrows indicate profiles, 4 km wide, where depth-frequency distribution of earthquakes are computed.

area of Friuli (Slejko *et al.*, 1989) which was involved in the seismic sequence beginning on May, 6, 1976 (Fig. 1). The data recorded by the O.G.S. seismic array show that actual seismicity is mainly distributed in this area (Slejko *et al.*, 1989).

3-D VELOCITY MODEL AND STRUCTURAL INTERPRETATION

The structural interpretation of the upper crust in the area is based on a three dimensional P velocity model obtained with Thurber's method (1981) of iterative simultaneous inversion of travel-time residuals from local earthquakes, as modified by Eberhart-Phillips (1986).

A starting velocity model, which constitutes the input for tomographic inversion, is defined on the nodes of a three-dimensional grid. The velocity at a given point (x,y,z) is obtained by linear interpolation between eight surrounding nodes. The travel-time hypocentre-station is estimated by the approximate ray tracing algorithm ART 2 (Thurber, 1983), which selects the minimum travel-time path connecting source and receiver. The solutions are obtained by an iterative process, first solving the hypocentre determination and then calculating the velocity anomalies. To control the end of the procedure, the significance of the solution variance between successive iterations is evaluated by an F-test.

The inhomogeneous distribution of sources and receivers in the investigated volume of the previous study (Bressan *et al.*, 1992) caused artifacts (smearing effects) in the inversion procedure, with consequent overestimate of velocity in some blocks of the grid. So, to improve the velocity model and to avoid smearing effects, we selected a different number of earthquakes with a homogeneous distribution over the investigated area. Moreover we changed the dimension of the grid by thikening the horizontal meshes in the central part. In this way we obtained a homogeneous distribution of sources and receivers, and an approximate equal density of ray paths in the investigated volume.

We used 467 local earthquakes recorded by at least 7 stations of the seismograph array of the Osservatorio Geofisico Sperimentale from 1984 to 1990, located with a HYPO71 program (Lee & Lahr, 1975), giving a total of 4532 P arrival times. Fig. 2 shows the seismograph array, the investigated area (grid 40 km x 60 km), and the epicentres location.

The seismic events inside the area bounded from 46.25 lat.N to 46.42 lat.N and from 12.93 long.E to 13.33 long.E were selected with quality A and B, horizontal error ≤ 1 km and vertical error ≤ 2 km. Outside this area the earthquakes were selected with quality A,B,C, horizontal error ≤ 1.5 km, vertical error ≤ 5 km. The starting model (five depth levels: 0, 3, 6, 9, 12 km) for the 3-D inversion is the same of Bressan *et al.* (1992). The velocity at 0 km depth is fixed according to different lithologies (limestones: 5.5 km/s, Flysch: 4 km/s, alluvial deposits: 3.5 km/s). All the velocity values were derived from DSS studies by the Italian Explosion Seismology Group & Institute of Geophysics, ETH, Zurich (1981).

In Fig. 3 a,b,c, isovelocity values of the tomographic inversion for profiles 2, 3 and 4 N-S of the grid (see also Fig. 1) are depicted.

For Stauber (1982) a tomographic inversion of good quality is indicated by homogeneity in the resolution. This is verified in our case study for the layers between 3 and 9 km depth.

For structural interpretation (Fig. 4 a,b,c) we take into account gradients in the velocity distribution, velocity inversions, the shape of isovelocity anomalies, together with the geological data of Castellarin *et al.*, 1979; Frascari *et al.*, 1978, 1979; Cavallin & Martinis, 1982).

Mesozoic limestones are characterized by Vp= 5.1-6

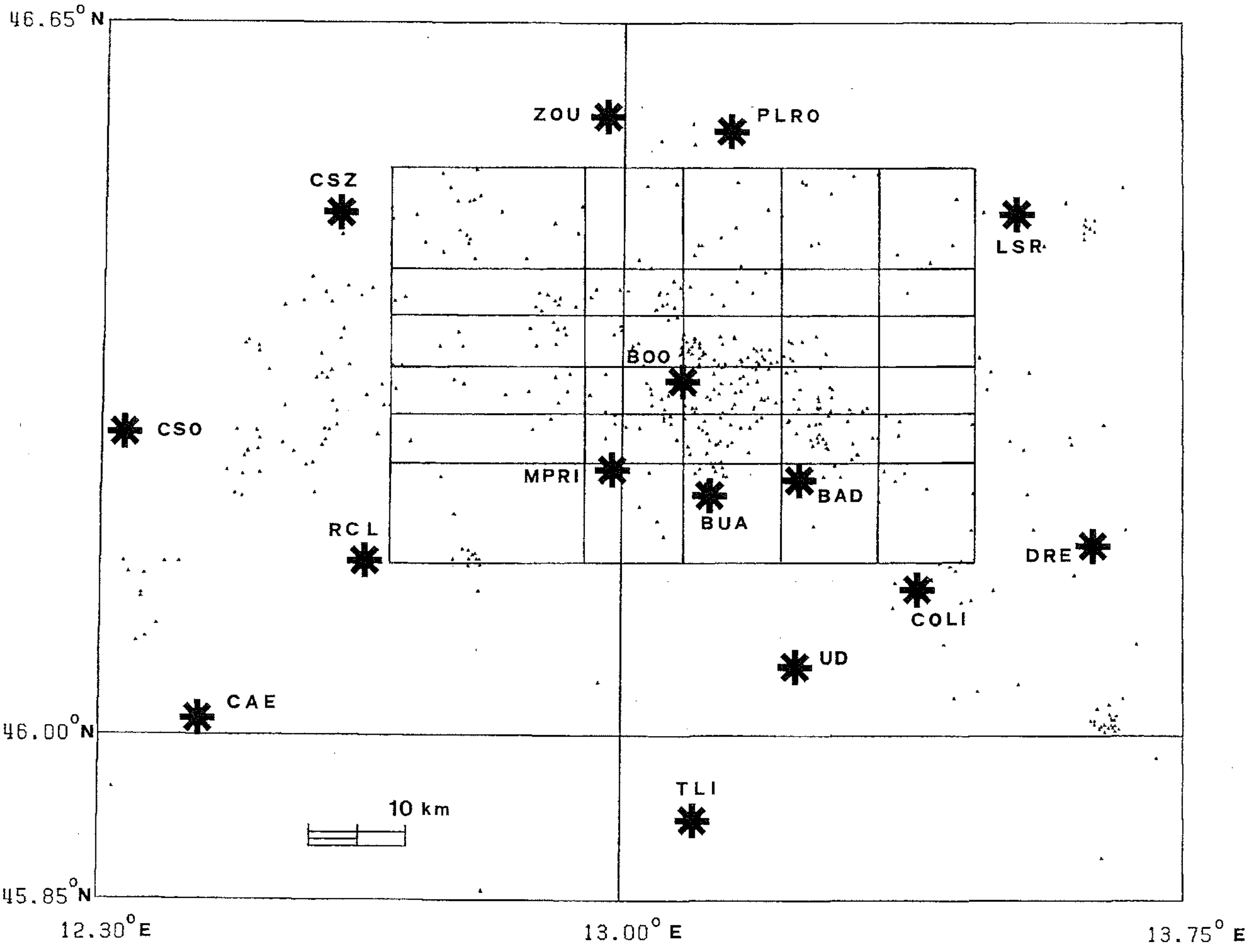

Fig. 2 - Earthquakes used in the tomographic inversion. Also shown are the stations of Friuli seismic network (asterisks) and the grid where 3-D velocity model is computed.

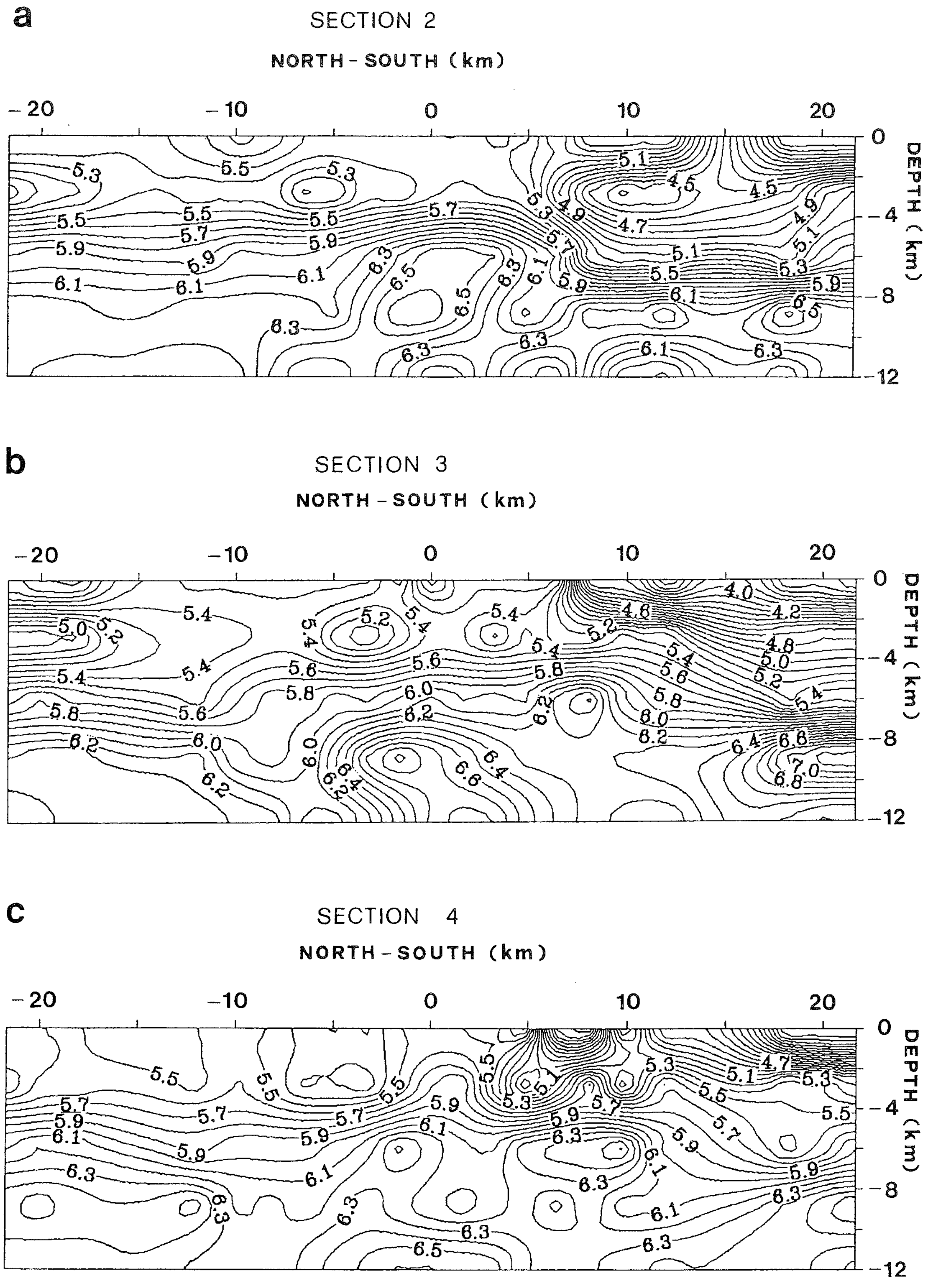

Fig. 3 - Vertical cross-sections of the 3-D velocity model. The location of cross-sections (grid) is shown in Fig.1. a) section 2 N-S; b) section 3 N-S; c) section 4 N-S.

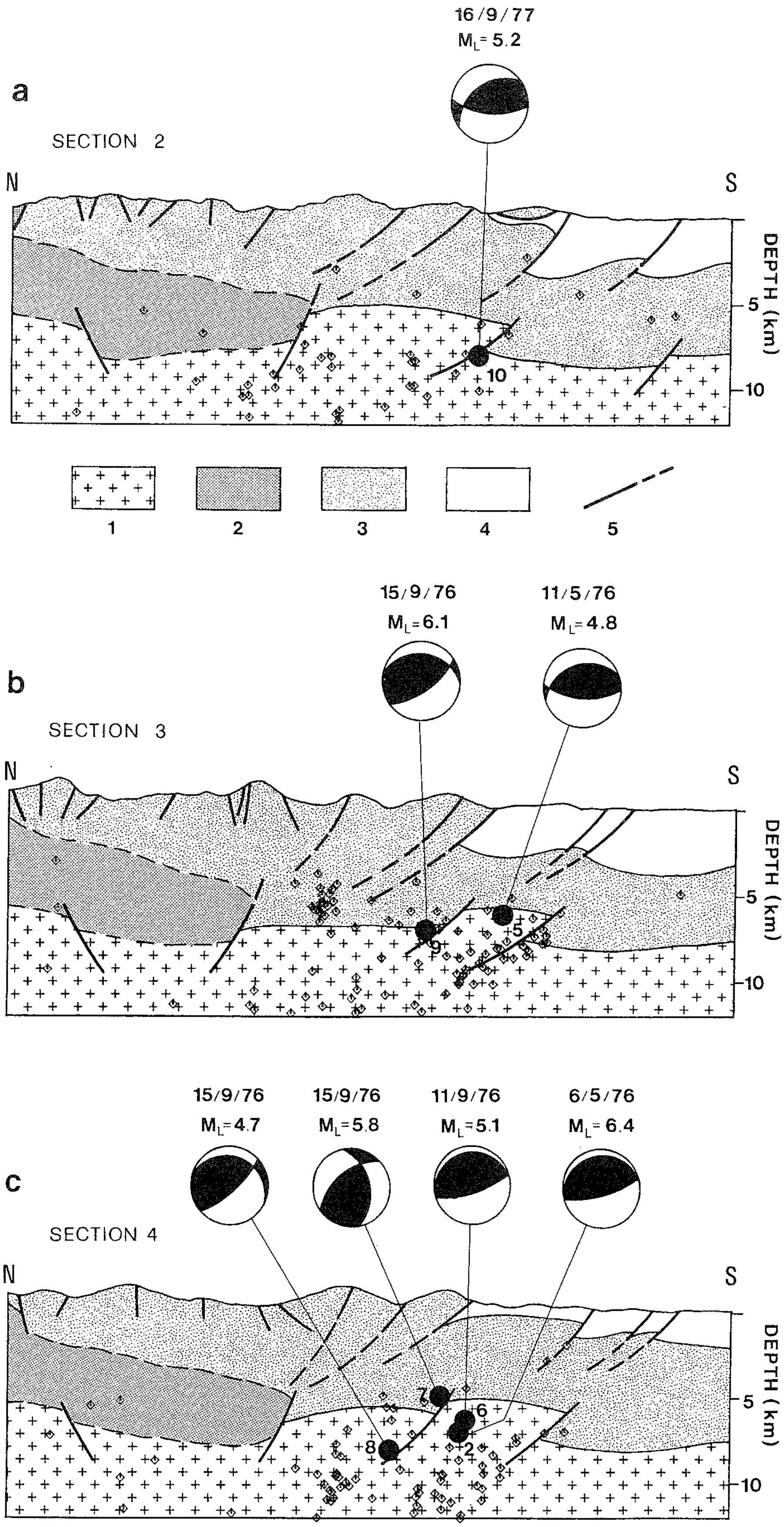

Fig. 4 - Geological N-S cross-sections with hypocentre distribution of the earthquakes used in the tomographic inversion and fault plane solutions of the biggest earthquakes of 1976-77 sequence. a) section 2; b) section 3; c) section 4. 1 = basement; 2 = Paleozoic sedimentary units; 3 = Mesozoic sedimentary units; 4 = Cenozoic and Quaternary deposits; 5 = faults.

km/s. Paleozoic terrigenous sediments (Vp= 4.9-5.8 km/s) are connected to the velocity inversion at 3 km depth in the northern sector. The flysch and molasse deposits are related to the velocity anomalies detected in the surface layers of the southern sector. At 6 km depth and more it is observed a high velocity body (Vp= 6.2-6.8 km/s), marked by strong velocity gradients, attributed to a complex of Paleozoic sedimentary deposits and metamorphic rocks, which we consider as basement. The velocity model does not allow a distinction between Paleozoic sedimentary series and metamorphic rocks. The high velocity body has been interpreted as a southward verging wedge affected by active faults, raised and thrusted, partly onto Mesozoic units. The cover constitutes an imbricate belt and is detached from the basement. In the last sector, some effusive volcanic bodies from the Triassic rifting may be locally present in the basement. The Paleozoic-basement contact (dashed in Fig. 4) is hypothesized on the basis of CASTELLARIN *et al.* (1979) and from gravimetric modelling; probably the transition is gradual.

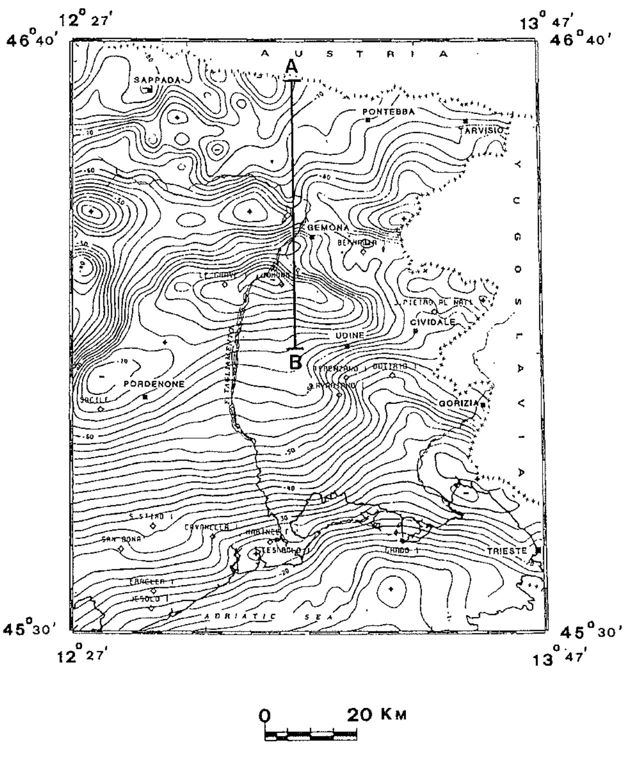

Fig. 5 - Bouguer anomalies of the Friuli area. A-B: trace of interpreted gravimetric profile (from CATI *et al.*,1987).

A N-S gravity anomaly profile (Fig. 5) was modelled from the Bouguer anomalies (CATI *et al.*, 1987) along N-S profile 3, taking the performed structural interpretation and including the effect of a northward dipping Moho (ITALIAN EXPLOSION SEISMOLOGY GROUP & INSTITUTE OF GEOPHYSICS, ETH, Zurich, 1981). The values of density are shown in Fig. 6b. The computed gravity field is in good agreement with the observed gravity anomalies (Fig. 6a), confirming the goodness of the geological interpretation, especially for the upper 10 km layers.

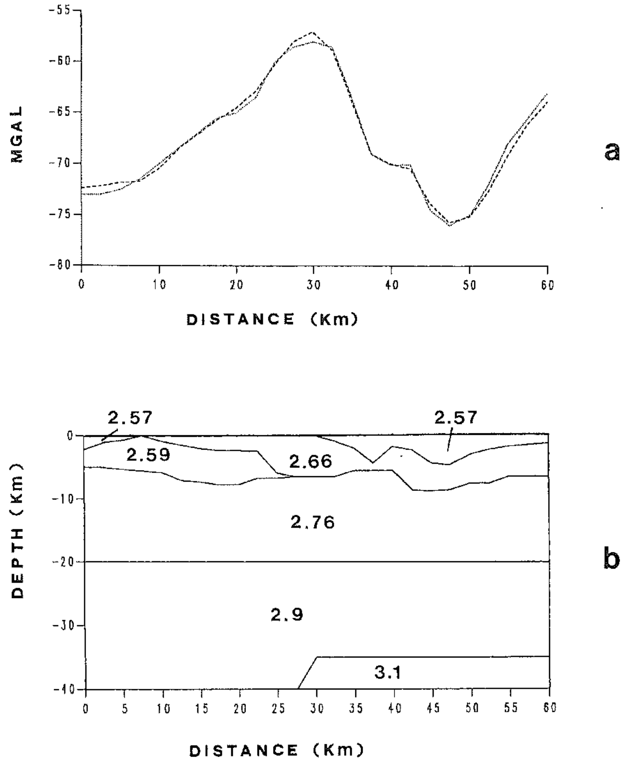

Fig. 6 - Gravimetric profile interpreted from Bouguer anomalies; the trace is drawn in Fig. 5; a) comparison between observed (dot line) and computed (hatched line) anomalies; b) density model with density values in gcm^{-3}.

SEISMOGENIC ASPECTS OF THE FRIULI AREA

The strongest earthquakes of 1976-1977 sequence (BARBANO *et al.*, 1985) are located inside the basement wedge and around the boundary with the Mesozoic series (Fig. 4 a,b,c). Their focal mechanisms (SLEJKO & RENNER, 1984; CIPAR, 1980; ANDERSON & JACKSON, 1987) are of thrust type, with a smaller strike slip component. Variations in dip and strike of the rupture planes suggest a structure of listric active faults inside the high velocity wedge. The geometric complexities of active faulting can be caused by the spatial variation of mechanical properties in response to applied stress and by the realignment of the stress field associated with the main rupture plane by conjugate and adjacent faults (KING, 1986; MENDOZA & HARTZELL, 1988). The earthquakes used in the tomographic inversion are mostly located inside the high velocity wedge (Fig. 4 a,b,c). Shallower seismicity located in the sedimentary cover is not clearly connected with the velocity model and probably represents the response to local stress inhomogeneties.

Most of seismic activity is limited to the uppermost 15 km of crust (BARBANO *et al.*, 1985; SLEJKO *et al.*, 1989). The depth earthquake distribution delimits the crustal layers where tectonic stress is mainly released through fracturing (brittle behaviour) from the regions where ductile aseismic deformation (creep) is prevailing (BONAFEDE *et al.*, 1982; SIBSON, 1983).

Creep becomes significant in quartz-rich rocks for temperature of about 300-400 °C and in feldspar-rich rocks at about 450-500 °C (SCHOLZ, 1988). The water content may enhance the creep behaviour of rocks in the ductile regime by the mechanism of pressure solution and hydrolitic weakening.

The shear resistance of the crust increases linearly with depth through the brittle regime to achieve a peak, beneath which it falls off exponentially (SIBSON, 1974). The maximum concentration of strain energy is related to peak shear resistance (SIBSON, 1974); the brittle/ductile transition is characterized by maximum background microseismicity (MEISSNER & STREHLAU, 1982; SIBSON, 1983). Probably, because of petrological crustal inhomogeneties, the boundary between brittle and ductile deformation is characterized by transitional behaviour over a few kms of depth.

We have compared the depth-frequency distribution of small earthquakes (2 ≤ M ≤ 3.5) recorded by the O.G.S. network from 1977 to 1989 (BRESSAN *et al.*, 1992), with the theoretical curves of shear resistance versus depth, in the central sector of Friuli (Fig. 1), which is affected by the maximum earthquake density (SLEJKO *et al.*, 1989). We selected earthquakes with maximum horizontal and vertical errors of ± 2 km.

Maximum concentration of seismicity is observed in the range 8-10 km depth; below 10-11 km the seismicity vanishes rapidly (Fig. 7).

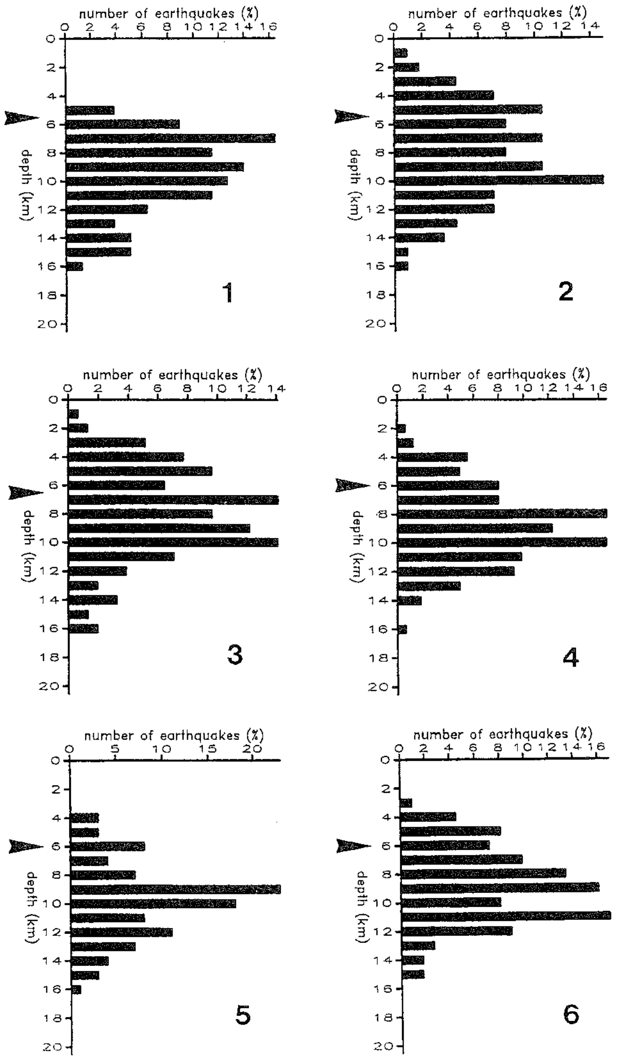

Fig. 7 - Depth distribution (per cent) of small events (2£M£3.5) computed for profiles 1, 2, 3, 4, 5, 6 of Fig. 1. The number of events are: 79 (1), 114 (2), 156 (3), 163 (4), 102 (5), 112 (6). Arrows mark the top of the basement wedge (from BRESSAN *et al.*, 1992).

For the comparison with the depth seismicity distribution, estimates have been made of maximum shear resistance and its variation with depth. Such estimates have to be considered a rough approximation of true behaviour, taking also in account the uncertanties in available creep laws (SMITH & BRUHN, 1984).

In the brittle regime, the maximum shear resistance is calculated (JAEGER & COOK, 1969; SIBSON, 1974) for thrust faulting (the predominate mode of faulting in the study area), with 0.36 the value of pore fluid factor. The values of density are 2.66 gcm^{-3} for sedimentary series and 2.76 gcm^{-3} for basement.

Stresses power law creep is calculated (SIBSON, 1977; 1983) for a prevailing dry quartz rheology with n=2.4, A=102 $GPa^{-n}s^{-1}$, Q=156 $KJmol^{-1}$, and for a prevailing wet quartz rheology with n=2.3, A=2·103 $GPa^{-n}s^{-1}$, Q=154 $KJmol^{-1}$ (RANALLI, 1987). Q is the activation energy, A and n are constants depending on materials.

The heat flow in the study area was extrapolated on the basis of the regional tectonic structure and a correlation between heat flow and the age of the last tectono-thermal event by CERMÀK & HURTIG (1979) who assigned the range values of 60-70 mWm^{-2}.

The depth temperature distribution is taken from CHAPMAN (1986) who calculated continental geotherms for various surface heat flow values. Figg. 8 a,b,c,d show the variation of calculated shear resistance with depth for thrusting, considering wet and dry quartz rheologies and two temperature gradients related to heat flow of 60 and 70 mWm^{-2} in the ductile regime. The depth earthquake frequency is related to shear resistance profiles for a wet quartz rheology, with strain rates between 10^{-14} to 10^{-15} s^{-1}, with a heat flow of 70 mWm^{-2}. The sharp decay of seismic activity from about 10-12 km depth occurs in corrispondence with a low velocity zone detected at a depth between 10 and 20 km depth by the ITALIAN EXPLOSION SEISMOLOGY GROUP & INSTITUTE OF GEOPHYSICS, ETH, Zurich (1981).

CONCLUSIONS

The 3-D P velocity model obtained from tomographic inversion shows in the Friuli area the existence of lateral and deep heterogeneties related to geological structures. The inversion is of good quality between 3 and 9 km depth.

A high velocity body is recognizable below 6 km depth in the central sector of the study area, interpreted as a southward verging thrust wedge of the basement, made up of Paleozoic sedimentary deposits and metamorphic rocks. The shape of velocity anomalies suggests that thrusted sedimentary cover is detached from the basement.

Most of the seismicity and the strongest earthquakes of the 1976-77 sequence are related to the high velocity body, which is characterized by a branching structure of thrust active faults.

Seismic activity in the sedimentary cover is lower than in the basement and it is probably caused by local stress inhomogeneties and by stress rearrangement following the main shocks in the basement.

The distribution of seismicity with depth reflects the

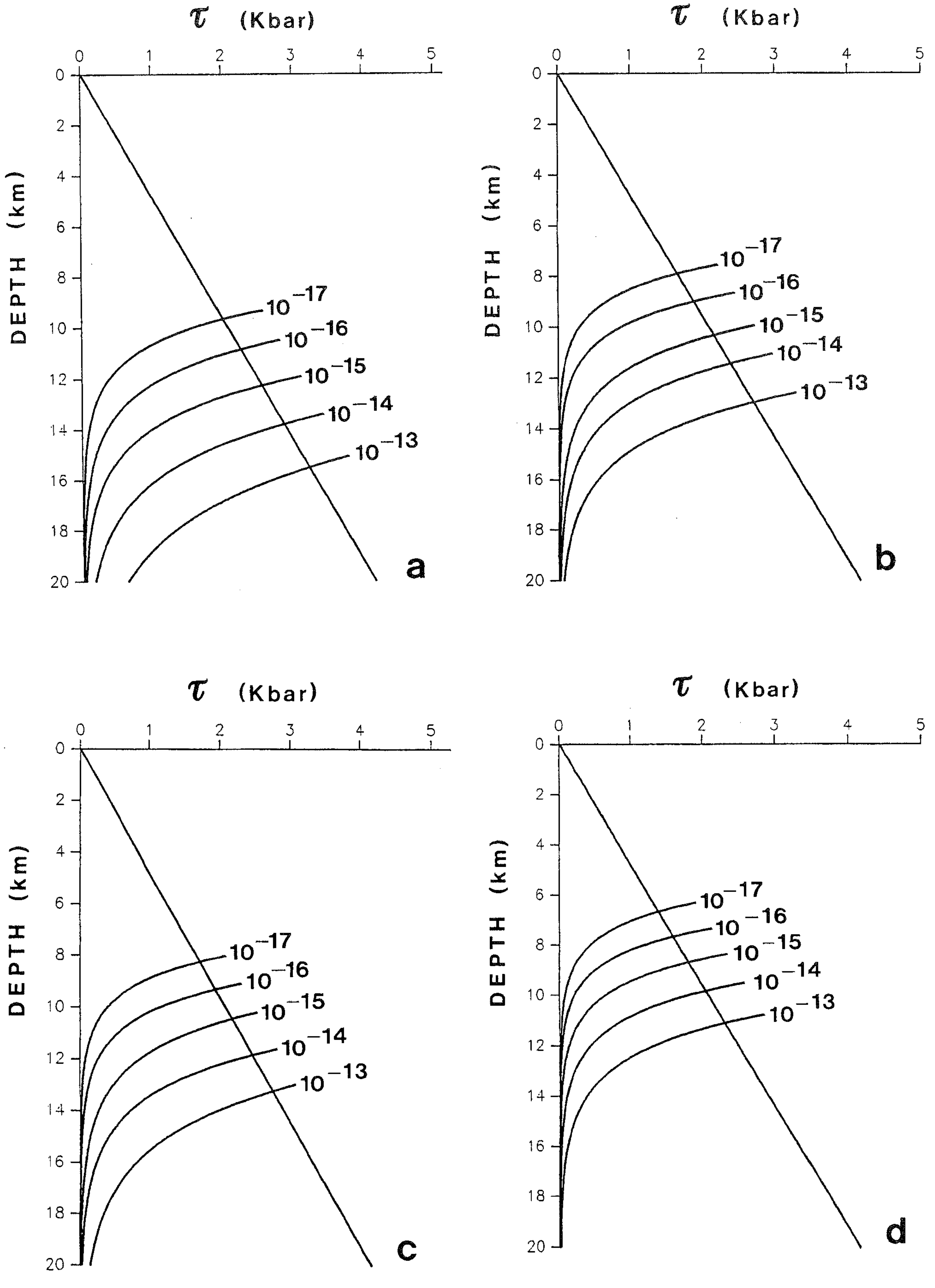

Fig. 8 - Shear resistance with depth for varying strain rates; a) dry quartz rheology, q (surface heat flow) = 60 mWm^{-2}; b) wet quartz rheology, q = 60 mWm^{-2}; c) dry quartz rheology, q = 70 mWm^{-2}; d) wet quartz rheology, q = 70 mWm^{-2}.

change from a brittle to a ductile mode of deformation, the transition occurring at about 10 km depth. The low velocity zone at 10-12 km depth in the crust may be related to the brittle/ductile boundary.

ACKNOWLEDGEMENTS

The seismograph network of Friuli is managed by Osservatorio Geofisico Sperimentale with financial support from the Regione Autonoma Friuli- Venezia Giulia. The authors wish to thank M.Ponton, S.Venturini & G.Tunis for discussions on geological features. Many thanks are due to Manuela Sedmach for drawing the figures.

REFERENCES

ANDERSON H. & JACKSON J. (1987) - *Active tectonics of the Adriatic region.* Geophys. J. R. Astr. Soc., **91**, 937-983.

BARBANO M.S., KIND. R & ZONNO G. (1985) - *Focal parameters of some Friuli earthquakes (1976-1979) using complete theoretical seismograms.* J. Geophys., **58**, 175-182.

BRESSAN G., DE FRANCO R. & GENTILE G.F. (1992) - *Seismotectonic study of the Friuli (Italy) area based on tomographic inversion and geophysical data.* Tectonophysics, **207**, 383-400.

BONAFEDE M., BOSCHI E. & DRAGONI M. (1982) - *A physical model of the long-period precursor to the 1976 Friuli earthquake.* Boll. Geof. Teor. Appl., **94**, 93-108.

CASTELLARIN A., FRASCARI F. & VAI G.B. (1979) - Problemi di interpretazione geologica profonda del Sudalpino Orientale. Rend. Soc. Geol. It., **2**, 55-60.

CAVALLIN A. & MARTINIS B. (1982) - *Gli scorrimenti del margine settentrionale della piattaforma carbonatica adriatica.* In: A. CASTELLARIN & G.B. VAI (a cura di), Guida alla geologia del Sudalpino centro-orientale. Guide Geol. Reg. SGI, 349-359.

CATI A. FICHERA R. & CAPPELLI V. (1987) - *Northeastern Italy. Integrated processing of geophysical and geological data.* Mem. Soc. Geol. It., **40**, 273-288.

CERMÀK V. & HURTIG E. (1979) - *Heat flow map of Europe.* In: CERMÀK V. & RYBACH L. (Eds.), Terrestrial heat flow in Europe Springer- Verlag, Berlin Heidelberg 1979.

CHAPMAN D. S. (1986) - *Thermal gradients in the continental crust.* In: DAWSON J.B., CARSWELL D.A., HALL J. & WEDEPOHL K.H. (Eds.), The nature of the lower continental crust . Geol. Soc. Spec. Publ. **24**, 63-70.

CIPAR J. (1980) - *Teleseismic observations of 1976 Friuli, Italy, earthquake sequence.* Bull. Seism. Soc. Am., **70**, 963-983.

DOGLIONI C. & BOSELLINI A. (1987) - *Eoalpine and Mesoalpine Tectonics in the Southern Alps.* Geologische Rundschau, **76**/3, 735-754.

EBERHART-PHILLIPS D.M. (1986) - *Three-dimensional velocity structure in Northern California Coast Ranges from inversion of local earthquake arrival times.* Bull. Seism. Soc. Am., **76**, 1025-1052.

FRASCARI F., VAI G.B. & ZANFERRARI A. (1978) - *Profilo carnico centrale. Nota illustrativa sommaria.* Rend. Soc. Geol. It., **1**, 15-17.

FRASCARI F., SEMENZA E., SPALLETTA C., VAI G.B. & VENTURINI C. (1979) - *Profilo carnico B: Gaital-M.S.Simeone. Nota illustrativa sommaria.* Rend. Soc. Geol. It., **2**, 17-20.

ITALIAN EXPLOSION SEISMOLOGY GROUP & INSTITUTE OF GEOPHYSICS, ETH, Zurich, (1981) - *Crust and upper mantle structures in the Southern Alps from deep seismic sounding profiles (1977, 1978) and surface wave dispersion analysis.* Boll. Geof. Teor. Appl., **92**, 297-330.

JAEGER J.C. & COOK N.G.W. (1969) - *Fundamentals of rock mechanics.* Methuen, London, 513p.

KING G.C. (1986) - *Speculations on the geometry of the initiation and termination processes of earthquake rupture and its relation to morphology and geological structure.* Pageoph., **124**, 3,568-585.

LEE W.H.K. & LAHR J.C. (1975)-HYPO71 (revised): - *A computer program for determining hypocenter, magnitude and first motion pattern of local earthquakes.* U.S. Geol. Surv. Open File Rep., 113 p.

MEISSNER R. & STREHLAU J. (1982) - *Limits of stresses in continental crusts and their relation to the depth-frequency distribution of shallow earthquakes.* Tectonics, **1**, 73-89.

MENDOZA C. & HARTZELL S. (1988) - *Aftershocks patterns and main shock faulting.* Bull. Seism. Soc. Am., **78**, (4), 1438-1449.

RANALLI G. (1987) - *Rheology of the Earth.* ALLEN & UNWIN, Boston, 366p.

SCHOLZ C.H. (1988) - *The brittle-plastic transition and the depth of seismic faulting.* Geologische Rundschau **77**/1, 319-328.

SIBSON R.H. (1974) - *Frictional constraints on thrust, wrench and normal faults.* Nature, **249**, 542-544.

SIBSON R.H. (1983) - *Continental fault structure and the shallow earthquake source.* J. Geol. Soc. London, **140**, 761-777.

SLEJKO D. & RENNER G. (1984) - *La sequenza sismica iniziata col terremoto del 6 maggio 1976 in Friuli.* In: Finalità ed esperienze della Rete Sismometrica del Friuli-Venezia Giulia. Regione Autonoma Friuli-Venezia Giulia, Trieste, p. 75-91.

SLEJKO D., CARULLI G.B., NICOLICH R., REBEZ A., ZANFERRARI A., CAVALLIN A., DOGLIONI C., CARRARO F., CASTALDINI D., ILICETO V., SEMENZA E. & ZANOLLA C. (1989) - *Seismotectonics of the Eastern Southern-Alps: a review.* Boll. Geof. Teor. Appl., **31**, 109-136.

SMITH R.B. & BRUHN R.L. (1984) - *Intraplate extensional tectonics of eastern Basin-Range: interferences on structural style from seismic reflection data, regional tectonics, and thermal- mechanical models of brittle-ductile deformation.* J. Geophys. Res., **89**, 5733-5762.

STAUBER D. (1982) - *Two-dimensional compressional wave velocity structure under San Francisco volcanic field, Arizona, from teleseismic P residual measurements.* J. Geophys. Res., **87**, 5451-5459.

THURBER C.H. (1981) - *Earth structure and earthquake location in the Coyote Lake area, Central California.* Ph.D. thesis, M.I.T., Cambridge.

THURBER C.H. (1983) - *Earthquake locations and three-dimensional crustal structure in the Coyote lake area, central California.* J. Geophys. Res., **88**, 8226-8236.

ZANFERRARI A., BOLLETTINARI G., CAROBENE L., CARTON A., CARULLI G.B., CASTALDINI D., CAVALLIN A., PANIZZA M., PELLEGRINI G.B., PIANETTI F. & SAURO U. (1982) - *Evoluzione neotettonica dell'Italia nord-orientale.* Mem. Sc. Geol., **35**, 355-376.