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Fault-Plane Solution of the Earthquake in Northern Italy, 6 May 1976, and Implications for the Tectonics of the Eastern Alps*

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Abstract. The fault-plane solution of the North Italian earthquake of May 6, 1976, has been constructed from long-period records of 37 stations (mainly WWNSS stations), assuming a focus in the crust. It is essentially a thrust type solution, the compressional axis having an azimuth of about 160°, perpendicular to the strike direction of the Eastern Alps. One nodal plane is very well defined from first *P*-wave motions: it is steeply dipping approximately SSE with a dip angle of 77°. The second nodal plane has been determined from *S*-wave polarisations at stations in the United States and Japan: it dips roughly NW with a dip angle of about 16°. The dip direction of this nodal plane is less well defined. From the two possible interpretations of the fault-plane solution, either a shallow thrust of Italy under the Alps or a steep thrust of the Alps under Italy, only the first one is geologically plausible. The slip direction of the underthrusting block (or plate?) has an azimuth of 348° and a dip angle of 13°.

Key words: Fault-plane solutions – Alpine tectonics.

Introduction

The earthquake of May 6, 1976, in Northern Italy was the first strong event in the Alps (magnitude 6.5 according to USGS) that occurred during the time of operation of the Worldwide Network of Standardized Seismographs (WWNSS) and was recorded with sufficient amplitudes all over the world by the long-period instruments of this network. Therefore, it is possible to construct a fault-plane solution for this earthquake from long-period WWNSS records. It is well-known from investigations of various other regions of the globe that because of their quality fault-plane solutions based on WWNSS data are essential pieces of evidence for the present tectonic activity of the earth, and that they have greatly contributed to the construction of the main features of the theory

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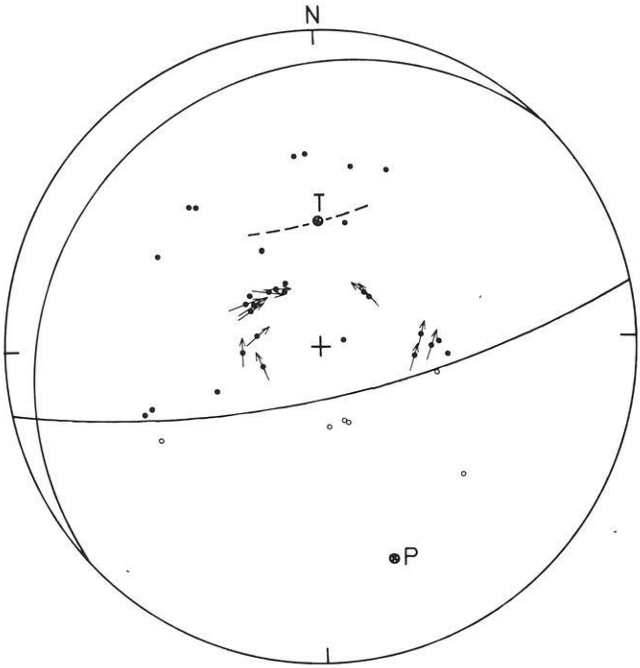

Fig. 1. Fault-plane solution of the North Italian earthquake of May 6, 1976 (equal area projection of the lower focal hemisphere). Dots (circles) indicate first P-wave motion away from (towards) the focus. Arrows indicate initial *S*-wave polarisation. The dashed line is the locus of the tensional axis, as following from the well-determined almost vertical nodal plane alone. The tensional axis chosen (symbol *T*) is in optimum agreement with the *S* polarisation directions. This determines the second nodal plane and the compressional axis (symbol *P*)

of plate tectonics. A fault-plane solution of the North Italian earthquake can therefore be expected to be of some importance for discussions of the tectonics of the Alpine-Mediterranean region and the complicated transition from the African to the Eurasian lithospheric plate (McKenzie, 1972; Ahorner et al., 1972; Gutdeutsch and Aric, 1976).

Fault-Plane Solution

For the construction of the fault-plane solution the epicentral coordinates 46.31° N and 13.31° E and a hypocenter in the crust have been assumed, in agreement with the determinations of the Centre Séismologique Européo-Méditerranéen at Strasbourg. *P*-wave radiation angles at the focus were calculated for a *P* velocity of 6.5 km/s, and *S* waves were assumed to have travelled along the same path as *P* waves. The fault-plane solution in Figure 1 was constructed from records of the following 35 WWNSS stations and 2 additional stations (Faro, Portugal, and Funchal, Madeira, operated by the Institute of Geophysics ETH, Zürich, Switzerland):

Station			AAM	ATL	ATU	BHP	BKS	BLA	BUL	COP
Distance (deg)			65	71	11	86	87	66	68	9
Azimuth (deg)			306	299	134	278	326	300	164	357
COR	DUG	ESK	GDH	GOL	KEV	KON	LPB	MAL	MAT	MSH
82	81	14	39	78	24	13	96	16	84	36
330	321	316	329	316	12	352	252	240	42	90
NDI	NUR	OXF	POO	PRE	QUE	RIV	SHI	SHK	STU	TAB
52	16	74	57	73	44	146	37	83	4	26
86	21	303	98	166	92	84	105	47	311	97
TOL	TRN	UME	VAL	WIN	Faro	Funchal				
14	72	18	16	69	18	37				
249	266	10	298	176	252	250				

One of the two nodal planes of the fault-plane solution is very well determined from the first *P*-wave motions alone. Figure 2 gives a few examples of vertical-component seismograms from stations relatively close to this nodal plane. The *P*-wave data at hand, however, do not restrict strongly the orientation of the second nodal plane, and, considering the WWNSS station distribution, it is unlikely that further *P*-wave data will do so.

Therefore, the *S*-wave polarisation at stations with epicentral distances between 44° and 96° was investigated in order to determine the tensional (*T*) axis and from this the second nodal plane. Figure 3 shows several horizontal-component seismograms, including examples from stations important for the purpose of fixing the *T* axis, namely stations in Japan (SHK, MAT) and the United States (BLA, OXF, DUG). The epicentral distances are large enough such that (1) linear polarisation of *S* can be expected (Nuttli and Whitmore, 1962) and (2) *S*-coupled PL where it exists is sufficiently separated from *S*, as for instance at BLA in Figure 3. At SHK, MAT and DUG interference of *S* and SKS is possible and therefore, depending on the amplitudes of SKS, a certain deviation of the true polarisation angle of *S* from the polarisation angle, following from the amplitudes indicated in Figure 3. At LPB which is situated close to the first nodal plane there is practically no SV energy which is demonstrated by the absence of SKS (theoretical arrival time 20:24:24 according to the Jeffreys-Bullen Tables). *S* and ScS which arrive almost simultaneously are of SH type alone, and the *S*-wave polarisation can be determined from their superposition.

In Figure 1 the possible locations of the *T* axis, as following from the first nodal plane, are indicated by the dashed line. This line is part of the intersection of the lower focal hemisphere and a cone of half apex angle 45° around the direction to the pole of the first nodal plane. In the neighborhood of the *T* axis the *S* polarisations should be directed towards the *T* axis. From this condition the most probable point on the dashed line is selected which fixes, finally, the corresponding compressional (*P*) axis and the second nodal plane. Because of the uncertainties in the *S* polarisations and hence in the *T* axis this nodal plane is not determined with the same precision as the first one. In particular,

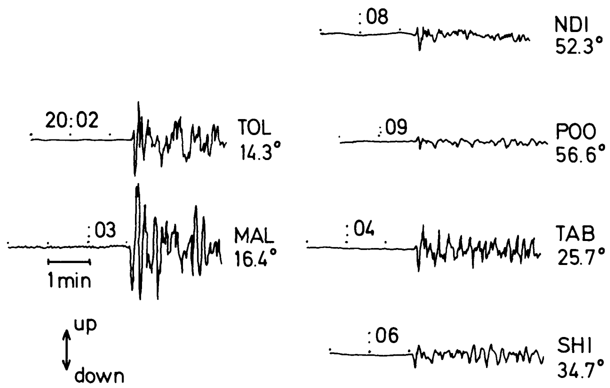

Fig. 2. Long-period vertical-component seismograms of the *P* wave at the WWNSS stations TOL, MAL, NDI, POO, TAB and SHI, showing the reversal in sign across the first nodal plane. The amplitude scale is the same for all traces. The numbers below the station codes are the epicentral distances

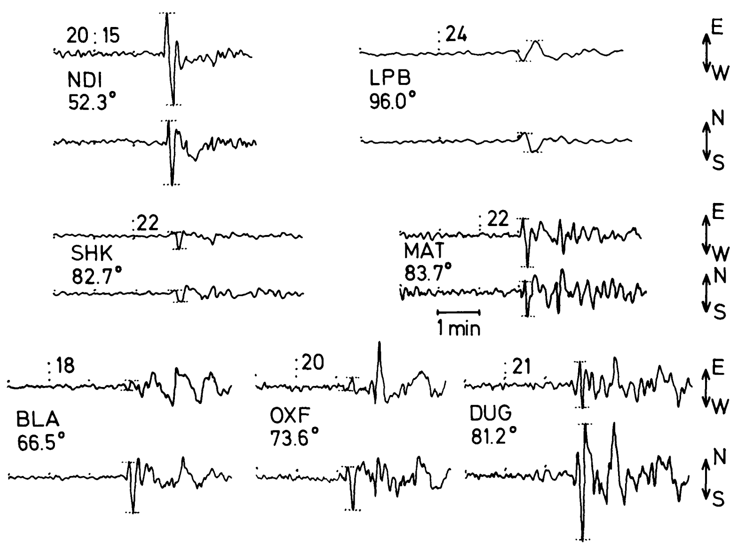

Fig. 3. Long-period horizontal-component seismograms (E–W and N–S) of the *S* wave at the WWNSS stations NDI, LPB, SHK, MAT, BLA, OXF and DUG. The peak-to-peak amplitudes that have been used for determining the *S*-wave polarisation are between the dotted horizontal lines. The amplitude scale is not the same for all stations. The time scale of LPB is extended by a factor of 2, compared with the other stations. The sign of the N–S component of NDI has been reversed, since only then the first *P*-wave motion is directed southwards, as it should be

its dip direction which in Figure 1 is about NW could probably have any direction between WNW and N. The parameters of the fault-plane solution in Figure 1 are:

	Azimuth (deg)	Dip angle (deg)
Pole of first nodal plane	348	13
Pole of second nodal plane	137	74
P axis	163	29
T axis	0	58

Discussion

The fault-plane solution represents essentially a thrust mechanism, unlike most of the solutions of earlier (and weaker) earthquakes in the Alps which are predominantly of strike-slip type (Ahorner et al., 1972). The mechanism is either a shallow underthrust of Italy under the Alps along the second nodal plane or a steep underthrust of the Alps under Italy along the first nodal plane. The nonuniqueness can be resolved, in the present case, by geological arguments: it seems that only the first kind of relative displacement is in agreement with the fact that the Alps exist and are uplifted at present, at least in parts, by rates of about 1 mm per year (Senftl and Exner, 1973; Jeanrichard, 1975; Schaer et al., 1975; Gutdeutsch and Aric, 1976). The slip direction of the underthrusting block which agrees with the direction to the pole of the first nodal plane has an azimuth of 348° and a dip angle of only 13°; it is not influenced by the uncertainties in the orientation of the second nodal plane. It could be difficult to find clear geological evidence at the surface for motions on this shallow thrust fault, directly related to the earthquake, even if the rupture has reached the surface. However, it is known, partly from borehole investigations, that in the focal region quite often Eocene-Paleocene sediments are found below the older main dolomite of the Calcareous Southern Alps, the layers dipping shallow to the north on the average (Martinis, 1975). This situation is most plausibly explained by underthrusting from the south, in excellent agreement with the fault-plane solution of the North Italian earthquake.

The older explanation of the reversed layering, overthrusting from the north due to gravitational sliding during a phase of rapid uplift of the Alps, is physically much less plausible. Moreover, it requires a complicated history of the Eastern Alps with considerable changes in the tectonic stress field in order to explain rapid and slow (or vanishing) uplift, tilting of the overthrusted layers and their substratum to the north, and the earthquake.

The interpretation of the *P* axis of the fault-plane solution faces the usual problem that in general the direction of the *P* axis agrees only approximately with the direction of maximum principal tectonic stress. Nevertheless, in the present case its azimuth is almost perpendicular to the strike direction of the Eastern Alps, and it is certainly safe to conclude that the maximum principal stress is also directed more or less perpendicular to this strike direction. Hence, the forces that caused the North Italian earthquake are the forces that folded and still fold the Eastern Alps. Furthermore, the agreement between the azimuths of the *P* axes of many well-investigated earthquakes in Southwest Germany (Schneider et al., 1966; Bonjer, 1976) and the North Italian earthquake indicates a rather homogeneous compressional stress field at least through the Eastern Alps and Southwest Germany, the compressional direction having an azimuth of about 160°.

Finally, it is worth noting that the underthrusting mechanism of the North Italian earthquake fits well into the speculative picture which McKenzie (1972, Fig. 13) has given of the plate-tectonics situation around the Adriatic. He tentatively assumed that the Adriatic is a tongue-like continuation of the African plate whose boundary runs NW through Italy, bends in the Eastern Alps and continues towards SE through Yugoslavia and along the west coast of Greece. The Adriatic is assumed to move NW, relative to the Eurasian plate, which would produce converging motions of the two plates in the focal region of the North Italian earthquake, in agreement with its fault-plane solution. However, McKenzie's hypothesis is certainly not the only one in the framework of plate tectonics which is compatible with the fault-plane solution derived here. It may also be questionable to apply the idea of relatively sharp plate boundaries to the Alps. Rather the extensive underthrusting in the focal region of the North Italian earthquake and a similar situation at the northern boundary of the Alps, which may be interpreted as underthrust of the Molasse under the Calcareous Northern Alps, could indicate a *broad* collision zone of two plates. The plate motions could be predominantly horizontal and convergent at the southern and northern boundaries of the Eastern Alps. In the central parts of the Eastern Alps and below a certain depth motions could be directed more or less vertically downwards. Above this depth uplift and folding would take place. Should these speculations be correct, then they would imply that a considerable amount of the relative displacement occurs by creep, since the seismic activity of the Alps is restricted to depths less than about 40 km (Ahorner et al., 1972; Gutdeutsch and Aric, 1976). This, in turn, would probably require rather high temperatures already in the crust.

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