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ACTIVE OR PASSIVE SUBDUCTION AT THE CALABRIAN ARC

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ABSTRACT

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The comprehensive list of earthquakes with focal depth ⩾ 50 km in the subduction zone of the Calabrian Arc is presented. The seismic zone dips towards the NW and strikes from SW-NE in the upper part to S-N at the deeper levels down to 490 km. The main activity occurs between depths of 220 and 350 km; relative minima are found above and below. The focal mechanisms of the earthquakes show a common feature in the position of one of the possible fault planes, and are indicative of a common stress pattern for the whole zone below 200 km.

Subduction in the mantle is of the passive kind and seems to be determined by gravity only. This is not yet clear for the horizontal movements which in the first place generated the zone of subduction.

INTRODUCTION

Active subduction occurs where a moving oceanic lithosphere plate underthrusts a neighbouring plate and plunges down into the earth's mantle. Generally, the motion direction of the diving plate coincides with its dip direction. The active horizontal drift of the plate is transferred into a plunging motion, and subduction in this case can be considered a direct extension of the lithosphere plate motion observed at the surface of the earth.

Passive subduction occurs where a continental plate or island arc actively rides or thrusts over a neighbouring oceanic plate. The oceanic plate is pushed down into the mantle under the edge of the moving continental plate or arc, and sinks down under its own weight. The older, cooler and denser the oceanic lithosphere is, the more rapidly it sinks and, also depending on the velocity of overthrusting, the steeper the zone will be. Active forward overthrusting and related passive subduction may occur by the motion of a massive continental plate or through an extension of a marginal sea by rifting behind the moving arc.

In most cases the process of subduction is a mixture of both active and passive effects (CHASE, 1978).

Apart from the general structure and tectonics of the region, also the morphology of the subduction zone and the earthquake focal mechanisms are important for the determination of the type and character of subduction. In the following some of the seismic aspects of the problem are considered for the subduction zone of the Calabrian Arc-Tyrrhenian Sea.

MORPHOLOGY OF THE SUBDUCTION ZONE OF THE CALABRIAN ARC

The only realistic delineation of subduction zones as yet is based on a detailed positioning of earthquake foci. Table I gives the sofar most complete and up-to-date data set of earthquake foci with a depth ⩾ 50 km for the region 36.5-42.5°N, 11.5-17.5°E. The material has nearly doubled since a former compilation by the same author in 1971.

The accuracy of the data of the list increases with the number and reliability of the reporting stations and thus in general increases with time. For part of the material this is reflected in the decreasing values of standard deviation SD of

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Table I

List of known earthquakes of focal depth ⩾ 50 km in the geographical block 36½-42½°N 11½-17½°E. Sources are indicated. Magnitude values are those of Karnik (1969) for the years 1910-1955, and of Rothé (1969) for 1956-1963. For 1964 and later years m_b values are given reported by the various agencies.

YeMoDa	h.m.s.	°N	°E	depth km	m	no. of stations used	S.D. sec.
Gutenberg & Richter (1954)							
100801	1040.4	39	15	200±	6.8		
110405	1528.2	40	15½	200±	6.3		
re-locations on basis of ISS data (Ritsema, 1971)							
150113	065244.3	41.74	13.72	93	6.8	19	4.11
150707	164255.8	40.30	15.27	326	5.9	17	5.27
170612	184246.6	39.38	16.57	76	5.3	8	3.78
260817	014255.3	38.92	14.98	56	6.0	34	3.65
280307	105509.0	38.33	15.99	81	6.6	62	2.98
300723	135313.4	40.42	15.07	112	4.6	14	3.71
330926	033325.6	41.96	14.01	57	5.5	50	3.75
370802	102401.3	38.94	14.37	188	4.5	13	4.09
371017	095913.0	39.40	14.88	319	5.8	35	2.57
380413	024549.1	39.33	15.13	277	7.1	133	2.43
410316	184825.5	38.71	12.09	62	6.2	31	4.11
430917	033922.3	39.69	15.52	300	5.5	13	1.84
460403	170149.9	39.12	14.91	319	4.2	11	1.77
470226	054238.5	38.88	14.83	276	5.0	19	2.18
470731	075448.5	39.04	15.44	278	5.6	39	2.28
470901	221858.6	39.77	15.50	312	5.2	23	2.09
500905	040440.2	42.47	13.11	72		24	3.36
520910	041704.0	38.86	15.55	220	5.3	22	1.99
521226	235557.1	39.92	15.43	280	6.2	95	2.02
530730	115257.1	38.97	16.17	289	5	12	1.73
540806	192117.4	40.53	16.00	68	4.8	43	3.22
541123	130005.9	38.61	15.11	238	5.8	52	1.99
550217	193133.5	39.64	13.32	457	5.6	43	1.52
560201	151051.6	39.07	15.58	235	6.4	99	1.99
591223	092902.6	37.71	14.38	59		96	2.36
600103	201934.3	39.27	15.31	281	6.2	132	1.93
ISS-Bulletins							
610506	160443	37.89	11.09	79		74	3.19
620325	213826	39.12	14.55	343		69	1.48
630601	203605	38.65	14.93	250		89	2.35
BCIS-Rothé							
630726	092646.4	39.6	15.2	337			
ISC-Catalogues							
640414	063527.0	38.84	14.78	293	4.3	40	
641004	014650.4	39.12	15.45	242	4.6	34	
650312	201908.0	38.8	17.6	95	4.5	39	
650412	130638.4	39.1	14.1	53		8	
650529	132128.4	42.81	13.0	50		11	
650529	170852	42.6	12.0	67		10	
651219	091417.6	39.4	16.1	230	4.1	14	
651223	152906.9	40.53	14.87	310	4.6	65	
660203	132328.5	38.51	14.89	242	4.3	32	
660404	141045.4	38.32	14.52	55	3.8	4	
660420	013807	37.6	13.9	58		6	
670214	144226.2	38.45	15.06	258	4.2	29	
670602	202023.9	38.81	14.95	283	4.1	38	
670617	154301	41.7	15.9	51	4.3	32	
670907	140903.6	37.85	15.24	53	4.4	61	
671203	194946	42.4	13.2	59	4.4	28	

671209	030956.0	42.00	16.41	66	4.6	83	
680421	210948.0	39.82	14.88	320	4.1	65	
681001	163103.2	40.19	15.39	295	4.3	61	
681223	113441.7	39.78	17.10	51		35	
690329	014338.7	40.04	15.10	310	4.6	94	
690402	013802.2	38.98	15.24	263	4.7	132	
690413	054543.4	38.82	14.84	275	4.1	32	
690415	005652.8	39.69	14.95	319	4.0	19	
691012	185435.4	39.91	15.17	306	4.0	35	
691023	021247.9	38.61	15.27	244	4.2	38	
691208	044420.2	39.46	15.58	247	4.0	21	
691211	060055.2	39.39	14.85	295	4.1	15	
700129	110924.5	38.75	14.83	284	4.6	77	
700217	073202.6	39.83	15.92	273	4.1	38	
700402	212639.5	38.29	14.28	226	4.6	31	
700605	092056.1	39.18	15.54	267	4.3	54	
700629	142253.9	38.72	16.66	69		20	
700816	104522.1	37.88	16.46	53		54	
701127	091723	41.9	16.7	84		6	
710403	040356.5	38.86	15.10	283	4.1	39	
710425	043928.9	39.30	15.26	293	4.4	86	
710501	222010.6	39.67	15.29	292	4.1	53	
710821	035904.2	39.65	12.90	485	4.1	54	
720229	213218.6	42.02	15.20	57	4.1	39	
720523	110426.8	39.02	17.32	55		45	
721109	114716	40.3	13.3	455		23	
721124	043957	42.5	12.8	68		26	
730517	204313.0	39.28	15.96	127		13	
730811	235301.0	39.93	14.00	423		11	
731213	015706	39.8	15.64	274		18	
731229	174425.5	38.76	14.80	267	4.9	185	
740110	115333	38.86	14.83	337	4.0	36	
740121	201156	38.90	15.26	100		29	
740124	131923.4	39.85	14.58	360	4.2	103	
740125	004342	42.7	13.1	151		26	
740228	172249	41.1	15.3	178		22	
740722	071932.7	39.25	15.38	257	4.5	130	
740916	222241.8	38.55	15.58	83		18	
741021	144925.9	39.50	15.31	296	4.0	39	
750131	201958	39.7	17.4	69		6	
750412	164703.4	38.45	15.56	178	4.2	100	
750504	212755.1	39.47	13.37	438		18	
750730	030115.1	37.53	14.83	60		11	
750810	205550.9	38.53	15.60	197	4.6	86	
750823	174253.3	39.48	15.76	267		31	
750930	075035.0	39.67	14.90	303		19	
751105	074628.8	38.59	15.93	113	4.1	65	
751218	131319.0	38.8	15.78	189		30	
760403	043708.9	38.6	16.9	54		16	
760406	090858.2	38.75	16.07	110	4.8	51	
760516	125500	39±1.4	16±1.2	464±151		10	
NEIS-PDE							
760921	150150.6	38.84	14.70	302	4.9	89	1.1
761012	042608.0	37.84	13.07	57		14	1.0
770620	020411.4	39.25	15.82	267	4.2	11	0.8
770628	071249.3	38.63	14.71	261	5.3	144	0.9
770815	211032.5	38.85	16.98	54	5.0	70	0.9
771220	200416.3	38.55	16.62	193	4.7	40	1.2
771225	021111.3	40.41	12.94	482	4.5	40	0.7
771230	173508.9	40.00	15.42	283	5.6	205	1.0
771230	180851.3	39.99	15.40	295	4.4	66	1.0
EMSC-Peterschmitt (pers. comm.)							
781227	174611.8	41.11	13.55	398	6.3		

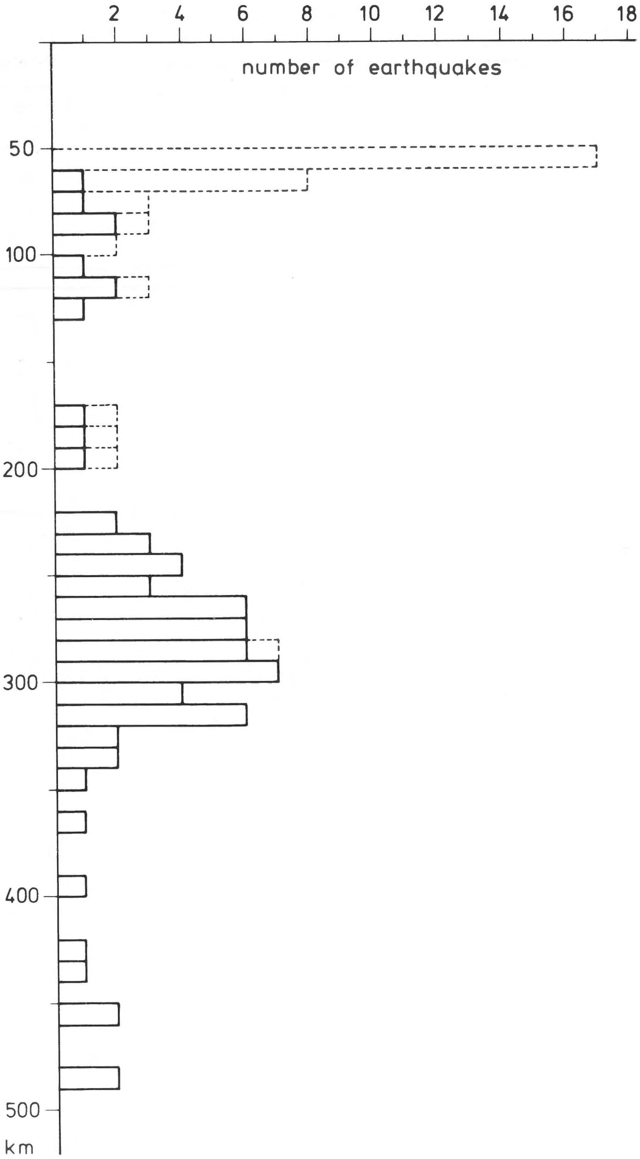

Fig. 1
Distribution of earthquakes in depth for the period 1915-1978.
Full line: Calabrian Arc zone s.s.
Broken line: the same, including all earthquakes of h ⩾ 50 km in block 36.5-42.5°N 11.5-17.5°E.

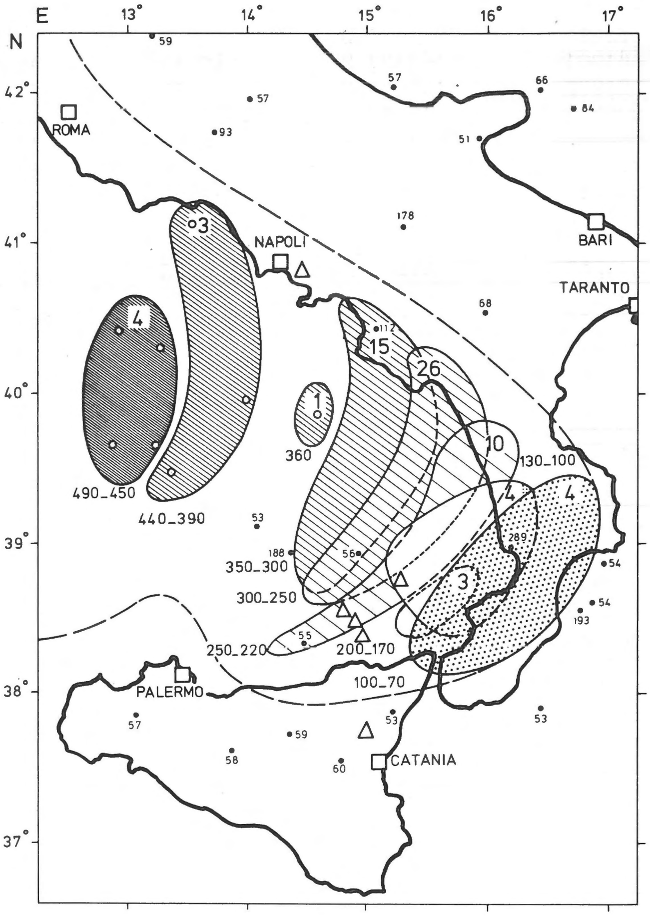

Fig. 2
The outline of the Calabrian Arc subduction zone. Depths are indicated in km. Total numbers of earthquakes are given inside the appropriate contour line. For the deeper levels the locations of the separate events are given in addition. Earthquakes falling outside the general scheme are plotted separately with a figure for the depth. Only earthquakes of depth ⩾ 50 km are considered of the period 1915-1978. Outside the dashed line the earthquake focal depth is normally < 70 km, inside in general > 70 km. Triangles indicate active volcanoes.

the observed traveltime minus the computed one. For the older earthquakes phase readings were less accurate as a consequence of an often insufficient time-service.

The parameters of the first two earthquakes of the list are those determined by GUTENBERG & RICHTER (1954). Since the original data used for the determination were not available these parameters could not be rechecked. Consequently, they are not used for the delineation of the morphology of the zone. The same holds for the earthquake of 1976.05.16, of which the parameters are very uncertain.

From 1960 onwards the epicenters of the International Seismological Summary were determined using a computer. To make the older material homogeneous all known 1915-1960 earthquakes of any focal depth in the block 36-43°N 11-18°E have been recomputed using the P and PKP data of the ISS bulletins as a data base and a computer program following that of Bolt (DE CROOK, 1967; RITSEMA, 1971). More than 100 events were reconsidered. In Table I only those with a depth ⩾ 50 km are given.

The data of the period 1961-1963 have been taken unchanged from the International Seismological Summary Bulletins, the entries for the years 1964-1976 from the Catalogues of the International Seismological Centre. The period July 1976 – December 1977 is covered by the Preliminary Determination of Epicenters issued by the USGS National Earthquake Information Service. There is one 1963 earthquake that only occurs in the Bulletins of the Bureau

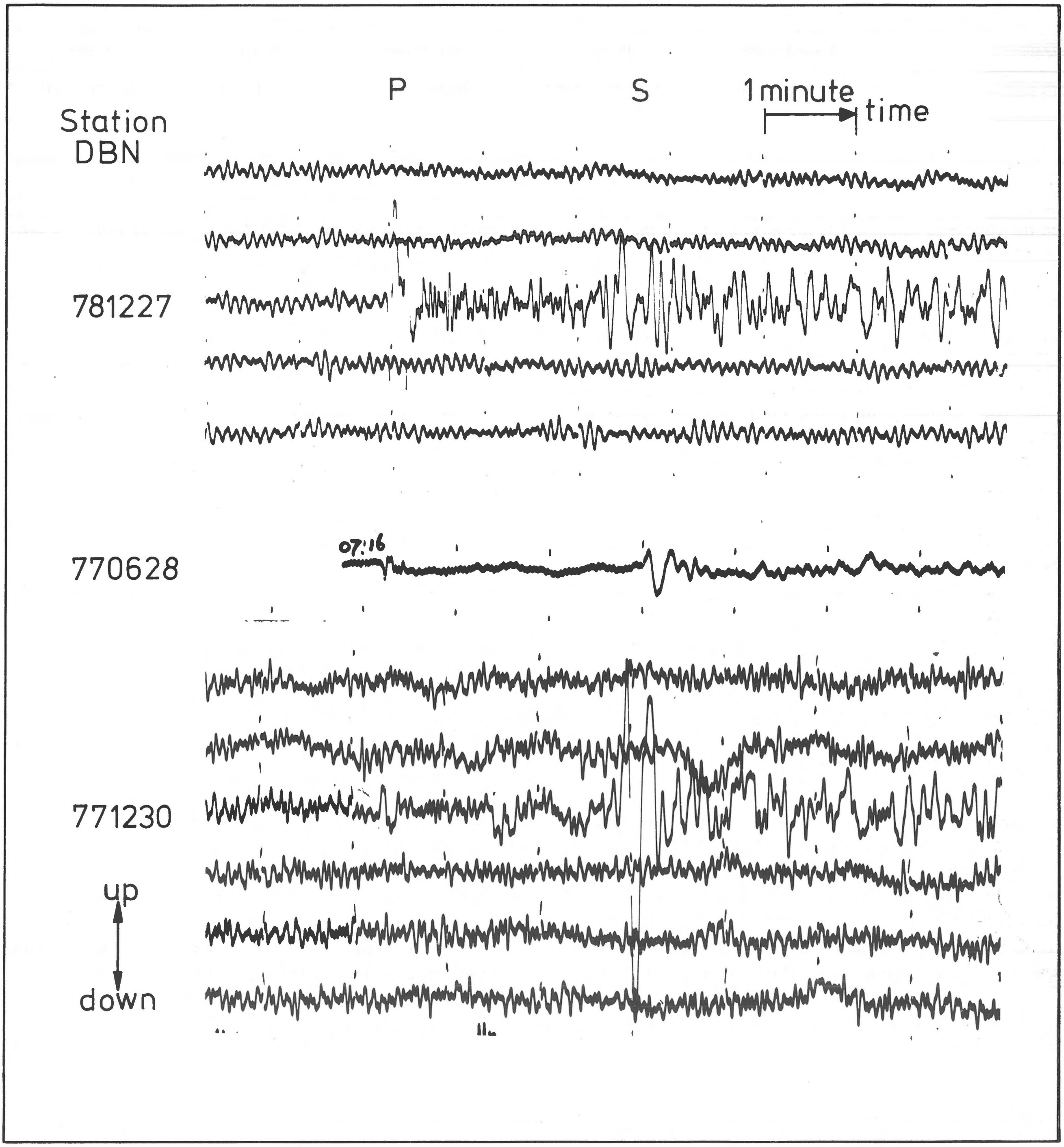

Fig. 3
Seismogram records of De Bilt station (30-90 Press-Ewing seismograph) of some recent earthquakes of the Calabrian Arc subduction zone. In the 781227 record, focal depth 398 km, the P wave is the dominating phase, in the 771230 record, focal depth 283 km, the S wave dominates the registration, and in the 770628 record, focal depth 261 km, P and S waves are of the same order of magnitude.

Central International de Séismologie, and the parameters of the last shock of December 1978 were supplied in a personal communication by E. Peterschmitt from the European-Mediterranean Seismological Centre.

The distribution of earthquake foci in depth is given in figure 1. More than 75% of the activity in the subduction zone proper is located between 220 and 350 km, with the highest concentration at depths of 260-320 km. In figure 2 the outlines of 30-50 km thick horizontal slices of the subduction zone are given as they are delineated by the location of

Table II
Earthquake mechanism solutions for earthquakes of the Calabrian Arc subduction zone. The azimuth and plunge of the various axes is given.

Date	A (or C)-axis		B-axis		C (or A)-axis		P-axis		T-axis	
Composite	N310°E,	0°	N220°E,	20°	N40°E,	70°	N330°E,	43°	N111°E,	43°
770628	310	15	214	20	75	65	335	56	114	27
771230	313	10	47	22	200	65	288	49	153	32
781227 (tentative)	305	0	215	40	35	50	337	33	93	33

NOTE:
In the composite solution data are incorporated of the earthquakes of 380413, 521226, 541123, 550217, 560201, 600103, 620325, 630601, 640414, 680421, 690329, 690402, 700129, 731220.

earthquake centres. Only a few spurious events indicated separately, do not fall within this general scheme. In general, however, the earthquakes show a clear grouping in an inclined zone dipping from under the Calabrian Arc in WNW direction under the Tyrrhenian Sea, in confirmation of earlier studies of PETERSCHMITT (1956) and the author (1971, 1972). The zone is about 200 km wide, stretching in NW direction over about 400 km and extending over a depth range from less than 70 km in the SE to nearly 500 km in the NW.

The zone seems to be divided into active parts separated by levels of reduced activity. Between depths of 120 and 220 km only 3 earthquakes are located in the zone, and between depths of 350 and 420 km only 2 shocks are found in the period of observations. Below 350 km depth the epicentres are more sparse and spread out both in depth and horizontally.

The deepest active part between 390 and 490 km with 7 earthquakes is elongated in North-South direction, the middle and principal part with 52 earthquakes between 220 and 360 km shows a transition from about S-N at the deepest levels to an about SW-NE elongation at the higher levels; the upper part between 70 and 120 km with 8 earthquakes strikes about SW-NE. The Northwestern dip of the upper part is about 30°, that of the main part is about 65° in the S and 45° in the N, and the deepest part dips about 45° to NW. This significant change of trend and dip of the zone could only now be ascertained after the substantial increase of data available for the later years.

THE FOCAL MECHANISM OF THE EARTHQUAKES

As has been shown earlier (RITSEMA, 1969), the data of several deep earthquakes of the zone in a composite plot can be used for a 'type' fault plane solution valid for the deep earthquakes of the region. There are indications, however, that the mechanism is not always exactly identical. Using the compression/dilatation data of the NEIS Earthquake Data Reports a provisional solution of the shocks of 1977.06.28 and 1977.12.30 were produced. There is a great similarity of these with the 'type' solution presented earlier. With this conformity in mind and the available seismic records of the De Bilt station we deduced, with the necessary reservations, a solution for the shock of 1978.12.27.

In Table II the different solutions mentioned are given, and in figure 3 the vertical component records of the long-period seismographs at De Bilt station of the two 1977 and one 1978 shocks are shown. Notwithstanding the great difference in seismic records – note especially the ratio of P and S wave amplitudes – the fault plane mechanisms have much in common (Fig. 4). In all solutions one of the possible fault motion directions is oriented horizontally or is slightly dipping in a WNW azimuth, and one of the nodal planes has a nearly vertical position striking about N40°E with a downward motion of the SE block relative to the NW block. Pressure axes are oriented in the general direction of the dip of the subduction zone. This type of mechanism seems to be valid throughout the zone in the depth range of 210 to 450 km.

It has not been possible to obtain mechanism solutions for earthquakes more shallow than 200 km. The few earthquakes of these depth levels in the past 10-15 years having large enough magnitude for the purpose, gave no clear solutions because of conflicting data. For older shocks the data were insufficient in number for reliable solutions. The shallow shocks of Apennines and Sicily typically show normal fault motions in the source (RITSEMA, 1975).

CONSIDERATIONS RELEVANT TO THE CAUSE OF SUBDUCTION

(1) Gaps or levels of reduced activity in the subduction zone are achieved either by a discontinuous process of subduction, or by the structural and physical conditions of the subducted lithosphere and surrounding upper mantle at the particular depth. It is impossible to make a definite statement on the age of the subduction zone. An instantaneous velocity of 1 cm/year, if assumed to be valid as an average for the past, produces high ages of more than 25-35 Ma for the most active part of the zone. It seems likely, therefore, that the subduction velocity in the past has been greater than 1 cm/year, at least for part of the period.

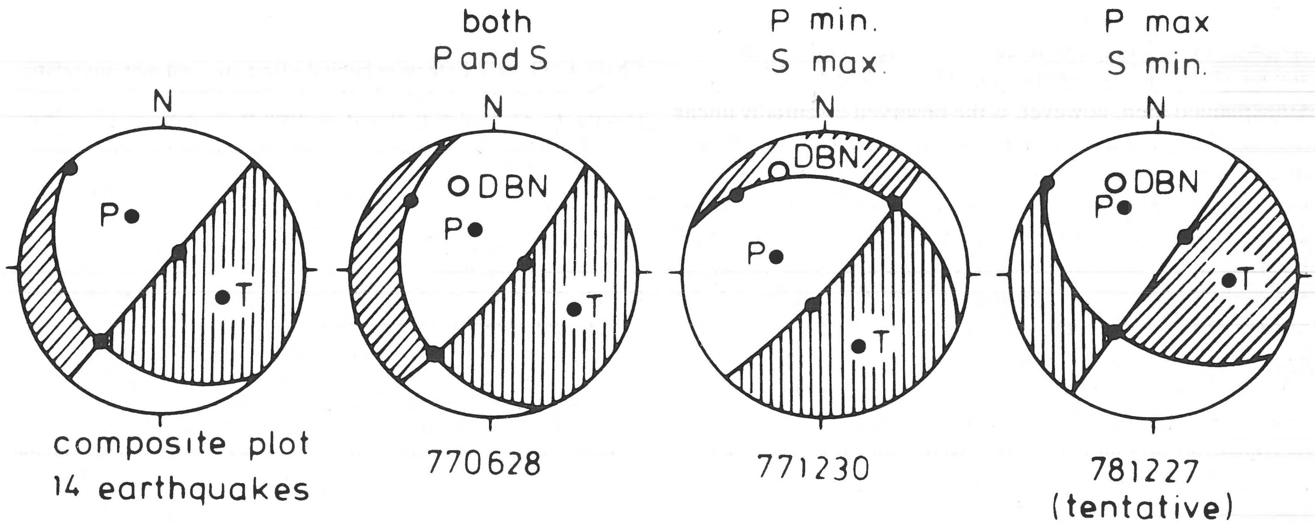

Fig. 4
Mechanism diagrams (lower focal hemisphere) of the earthquakes of Table II. Compression quadrants hatched, dilatations blank. The position of the De Bilt station, the records of which are given in the figure 3, is indicated in the diagrams.

(2) The change of trend of the zone with depth points either to a gradual change of drift direction of the arc during the generation of the zone, for example by an increasing influence in the form of a northward pressure of the African plate, or to a later distortion of the subduction zone by flow in the earth's mantle.

(3) The similarity of the earthquake focal mechanisms throughout the zone indicates a common stress pattern between depths of 200 and 450 km. This argues for a zone which is not disrupted into separate blocks. It also favours the flat-slab model against the more conical mode of origin around a centre deep in the Tyrrhenian subcrust as advocated originally by PETERSCHMITT (1956) and which is in line with the VAN BEMMELEN (1969) model with a rising mantle blister as the causative agent.

(4) Subduction of the active kind in WNW direction along the Calabrian Arc is incompatible with the SW-NE direction of subduction in the Hellenic Arc. The lithosphere involved in both cases belong to the internally rigid African plate. A sideways subduction by a northward motion of a triangular promontory of the African plate is in contradiction with the focal mechanisms in the two arcs (RITSEMA, 1969, 1974) which do not allow for such a common motion component of the subducted plate (Fig. 5). It is further observed that the seismicity of the Mediterranean zone between Azores and Eastern Anatolia is not a linear function of longitude as could be expected from global plate motions patterns (MINSTER & JORDAN, 1978). Great relative maxima are found at the longitudes of the Hellenic and the Calabrian Arc (RITSEMA, 1975), which only can be explained by a source for this seismicity independent of the local global drift pattern.

(5) Especially for the deeper parts of the zone thus only passive subduction is acceptable for the present, either by an eastward, later southeastward motion of the Tyrrhenian subplate, or by a fissuring and surficial extension and oceanization of the Tyrrhenian subplate, and a consequent piling-up of the Calabrian Arc structure in the ESE.

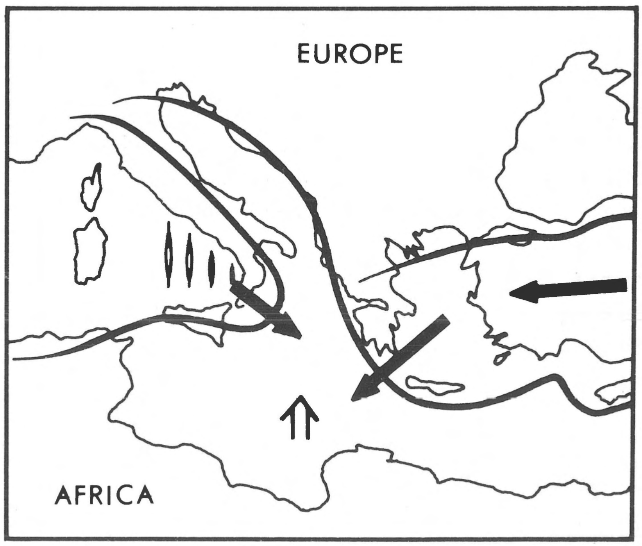

Fig. 5
Instantaneous relative movements between the European and African plates. Boundaries between the African plate, the Tyrrhenian and the Anatolian-Aegean blocks, and the European plate are indicated schematically.
Open arrow: motion direction of the African-relative to the European plate, magnitude of the order of 1 cm/year;
Full arrows: motion directions of the Calabrian Arc and of the Anatolian-Aegean block – Hellenic Arc over the African plate, magnitude of the order of several cm/year.

Generation of an independent motion of the Tyrrhenian subplate by a rising mantle blister, as suggested by VAN BEMMELEN (1969) is one of the possible models for the region. Unexplained then, however, is the observed essentially linear zoning of the subduction slab and the constancy of the focal mechanisms in the zone. VAN DEN BERG (1979) found on palaeomagnetic grounds that the Italian peninsula since about 25 Ma ago rotated over more than 25° from an original S-N position to its present SE-NW orientation. This could be reconciled with our conclusion of a W-E motion and extension of the Tyrrhenian area relative to the Ionian = African plate by a N-S fissuring of the crust and associated volcanic activity. A condition for this, however, is that the pole of rotation has to be situated in Tuscan or further North, just as suggested by CIVETTA ET AL. (1978), and not in the South near the isle of Malta as advocated by Van den Berg.

CONCLUSIONS AND REMARKS

It is still too early for a complete description and explanation of the presence and the mechanism of the Calabrian Arc earthquakes. It is clear, however, that subduction in this case is of the passive gravitational kind. Although gravity plays an important role in the tectonic process of subduction in the region, it cannot be concluded from these data that it is also the driving force for the world-wide process of ocean floor spreading and lithosphere plate drifting.

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This note has expressly been compiled to pay hommage to Rein van Bemmelen for his inspiring and stimulating influence in the course of a lifetime of solid earth studies on so many of his colleagues, students and friends from all over the world.

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