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SEISMOTECTONICS OF THE CARPATHIANS AND CENTRAL ASIA

A DISSERTATION SUBMITTED FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY AT THE UNIVERSITY OF CAMBRIDGE,
DEPARTMENT OF GEODESY AND GEOPHYSICS

CONSTANTIN ROMAN

PETERHOUSE
August 1973

PART 1. SEISMOTECTONICS OF THE CARPATHIANS

Institutul Geologic al României
Bucureşti – 1998

GEOLOGICAL INSTITUTE OF ROMANIA

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CONTENTS

Welcome ideas!

Each contribution to the Earth Sciences development represents a new "brick to the common house", irrespective of its timing. The paper of Dr. Roman is such a new brick, not only to the Earth Sciences house of Romania but to the whole Earth. It is a pleasure for us to have the possibility to publish this paper. In order to recover the "old" ideas of our colleagues, which work now abroad (the ideas and the colleagues) and are still valuable (the ideas) we decided to make efforts to collect them (the ideas) in Special Issues of our journals. Whatever the reasons were the distal position in the past should now be replaced by a proximal one in relation to our former colleagues. Not only from a pure human point of view but also from the point of view of assessing and enhancing communication with everybody working in the fields covered by our institute should the printing of this book be acceptable.

In order not to alter the primary form of Roman's thesis and the stacking sequences of his thinking the text is here reproduced as such, only with small shortenings. In such a way our contribution to the breaking down of "conspiracy of silence" seems to me to be decidedly greater and much more significant.

Let's have a look at the "time tunnel", particularly interesting from the point of view of one of the most revolutionary ideas of this century, i.e. the plate tectonics.

Prof. Dr. Gheorghe Udubaşa
Director General of the Institute
Member of the Romanian Academy

A FOREWORD

Having been invited by the Geological Institute of Romania to contribute a Foreword to the publication of the "Seismotectonics of the Carpathians and the Central Asia", a dissertation submitted for the degree of PhD (Cambridge 1973), it is my privilege, as Head of the Romanian Academy's Geonomic Section, to state that Dr Constantin Roman's dissertation represented at that time a contribution to the development of the geophysical approach of Plate Tectonics in general and of the Romanian territory tectonics in particular.

After his graduation as M. Eng. of the Institute of Petroleum, Gas and Geology in Bucharest (1966) - where professors were well known Romanian geoscientists as Sabba Stefănescu, Liviu Constantinescu, Ion Dumitrescu, Iulian Gavat - Constântin Roman was a Scholar of Peterhouse, the oldest Cambridge College, founded in 1284, which had amongst its members an array of distinguished scientists, amongst whom one could recall Cavendish, Kelvin, Dewar, Babbage and this century several Nobel prize winners.

Dr Roman's thesis comprises original work, carried out between 1969 and 1973 at the Department of Geodesy and Geophysics at Cambridge. During his first year at Cambridge, Mr. Roman's project leader, Dan McKenzie, entrusted his pupil with the sound principle of publishing as fast as possible in order "to secure the paternity of his ideas and preserve the scientific edge over his fellow scientists". This resulted in the article: "Seismicity in Romania - evidence for the sinking lithosphere" ("Nature", 223, 1176-1178). After only one year as a research student, this was a brilliant start, which subsequently brought the project supervision under Sir Edward Bullard, the father of Marine Geophysics. Roman's examiners were D.H. Matthews (of sea-floor spreading fame) and Hal Thirloway, Head of the Seismic Laboratory of the UK Athomic Energy Authority, Aldermaston and a world authority in monitoring Soviet Nuclear tests.

The first part of this thesis deals with the Seismicity of the Romanian territory. This is the first time that a computer program of statistical mathematics was used on a cluster of Romanian earthquakes in order to determine with greatest precision their location. The results revealed a new geometry of subcrustal foci, hitherto impossible to define accurately.

However, what is truly remarkable was the further refining of these seismic results (foci mechanism, fault plane solutions, travel-time residuals of P-waves) and the author's attempt of their interpretation in terms of Plate Tectonics, even if the geotectonic framework of his model was disputable. Dr. Roman's Plate Tectonics research was contemporaneous with the first Plate tectonics model of the Romanian Carpathians based on geological arguments (Rădulescu and Săndulescu Tectonophysics 16, 1973) and was quoted in important syntheses as "Plate Tectonics", Le Pichon et al., Elsevier, 1973, "The Making of the Earth" ed. Richard Fiefield, Blackwell Publ., 1985, "Pannonian Basin", ed. Royden et al., AAPG Memoir, 1987 etc, subsequently adopted world-wide, following the publication of his article "Buffer Plates, Rigid Plates, Sub-Plates - a comment on paper 'Active Tectonics in the Mediterranean' " (Geophys. J. Roy Astr. Soc., 33, 1973). Roman's article on the Tibetan and Sinkiang Buffer Plates was printed only weeks before Peter Molnar, of MIT, published his results.

The second part of this dissertation deals with the Hymalaian Seimicity. The relocation of the Central Asian earthquakes, the analysis of the magnitude versus the spatial distribution of seismicity, the focal mechanism and fault-plane solutions of major seismic events, led to the definition of the Tibetan and the Sinkiang buffer plates. This novel concept coined by Dr. C. Roman remains an important contribution to the Asian tectonics: "Buffer plates-where continents collide" (new Scientist, 57, 830, 180-181, London, 1973, reprinted in 1985). Other hyperseismic zones of the Eurasian continental crust were thus redefined, such as the Anatolian buffer and the Persian Buffer Plates, respectively, and this is now history.

The dissertation preserves a real interest for the Romanian School of Geophysics, which was provided with a foundation on which subsequent generation of researchers built some of their models. In this context Dr. Roman's contribution was recognised by the Senate of the University of Bucharest, which elected him an Honorary Professor and his International expertise in the field of Energy and Natural Resources was called upon being nominated a Personal Adviser of the President of Romania.

Taking into account the above noted considerations, I welcome the initiative of the Director of the Geological Institute of Romania, Professor Gheorghe Udubaşa, corresponding member of the Romanian Academy and the editing work of the Scientific Secretary of the Institute, Dr. Serban Veliciu, to publish Dr. Roman's Ph.D. thesis in recognition of his contribution to the advancement of Earth Sciences.

Acad. prof. dr. Mircea Săndulescu
Head of the Romanian Academy's Geonomic Section

EDITOR'S NOTE

Constantin Roman was lucky enough to be doing his research in Cambridge at a time when he "was led, at the right moment to follow a path trodden by very few and where each wayfarer was conspicuous. It is now a crowded path on which individuals cannot fail to jostle each other".

He worked on the Tibetan and Himalayan earthquakes under Sir Edward Bullard (himself remembered for his first ever mathematical reconstruction of the Atlantic, known as the "Bullard's Fit"). As a pupil of Bullard, Roman's name falls within a direct line of distinguished scientists of the Cambridge School of Physics, through Thompson, Rutherford and Cavendish, all the way to Sir Isaac Newton. As part of this tradition, Roman's research was going to alter the concept of Global Tectonics.

Constantin Roman's research led to a new tectonic solution of the occurrence of seismicity within the Continental Crust of Eurasia: this was fundamental in the development of Plate Tectonics theory at Cambridge and is *unique in several ways.*

First and foremost there is its scientific interest in the recognition of the existence of a new type of lithospheric plate - the "non-rigid plate" or "buffer plate", published in scientific journals. Several newly-defined "buffer plates" were carved out of large tracts of Continental Crust of Eurasia, in particular the areas behind the Himalayas - Tibet and Sinkiang, the outcome of which was going to have a huge impact on the theory of Plate Tectonics. Furthermore, the unexpected discovery of a then yet unknown piece of oceanic lithosphere sinking vertically under the Continental Crust of the Carpathians the results of which were published in "Nature " represented a contribution to the huge jig-saw puzzle of the reconstruction of Tethys. A few months later Dan Rădulescu and Mircea Săndulescu firstly reviewed the evolution of the Carpathians area as a collection of effects of the plate tectonics.

During the late sixties and early seventies, these new Global Tectonic concepts were going to revolutionise the understanding of our Planet Earth and in particular the effect of the collision of Africa, Arabia and India on Eurasia.

The number of researchers whom it did inspire is amazing - the first articles published in "Nature", the "Geophysical Journal" and the "New Scientist" remain among the classics of the specialist literature : these were the early, but heavy days when Vine and Matthews evolved the concept of "sea floor spreading" and the Canadian Tuzo Wilson, then a visiting Professor at Cambridge, devised the dynamics of "transform faults": it caused a frenzy of research which has since transformed Geology in a manner which has not been done before, or since.

It is nevertheless true that Constantin Roman's thinking, whilst it flourished in the stimulating Cambridge environment which represents the pinnacle of British Academia, would not have been possible without the broad culture which he received from the Romanian School of Geology and Geophysics, where he was nurtured, at the University of Bucharest, in the early 1960's. It is here that he obtained his MA in Geophysics with a first ever dissertation on "Palaeomagnetism of Complex Copper Ore Deposits of Dobrogea". This was an early hint that we got about Roman's future career, which was defined by his research Tutor Professor Liviu Constantinescu as having made "a significant contribution, showing both understanding and perseverance in solving a research problem".

Much more encouraging in discerning the potential talent in Roman's future input was the assessment of his dissertation examiner and erstwhile professor in Bucharest, the late Acad. Sabba S. Ştefănescu, who wrote:

"he managed to work out a very interesting and original diploma paper at the end of his fifth year of study..." "The paper was written so passionately and explained so beautifully that Mr. Roman was congratulated by his examiners".

It is perhaps ironic to consider the twists and turns of Constantin Roman's career, where he was led to excel in domains in which, at the beginning, he was not at all, to put it mildly, "at the head of the pack". He confided in me that, when he was 16, he "was not brilliant at Geology and Physics", only to end up reading Geophysics for his MA. Likewise, as his contemporaries at the Institute of Oil, Gas and Geology know it too well, Constantin's Roman's "forte" were most decidedly neither Tectonics nor, indeed, Seismology! Yet in spite of these inauspicious beginnings, at Cambridge, the topic in which he made his mark was "Seismotectonics". This success is undoubtedly qualified by the two traits of his character already mentioned by his professors, namely "perseverance" and "enthusiasm". To all these I should add a third one, which is crucial in our profession, that is "imagination" which he used in interpreting his research data and coming with unique solutions, often against all odds.

The result of his work at Cambridge has exceeded the expectations - as he described to me so vividly, on one of his visits to Romania, that "the birth of a new idea was drama of the highest order, as the tension mounted and mounted towards the final climax". This was the scientific "rat race" of the 1970's involving great scientists, such as D. H. Matthews, Fred Vine, Xavier Le Pichon, John Dewey, Peter Molnar, Dan MacKenzie, and many others, with their very human faults and foibles, their petty rivalries and driving ambition. Above all those who heard Constantin Roman's stories of his debut in Plate Tectonics at Cambridge they followed an extraordinary excitement of his desperate efforts to beat a group of researchers from the Massachusetts Institute of Technology to the solution to one of the great enigmas of Earth Sciences - the seismicity of Central Asia. Cocooned in his Cambridge microcosm and obsessed by his research, Roman was oblivious of Peter Molnar's trans-Atlantic team from MIT working for years on the same Tibetan earthquakes and accumulating a mass of information, which was about to be published.

This sudden realisation came as a shock, as the very object of his hard-won evidence, which make the core of his doctorate was put in jeopardy should the American colleagues publish first their results.

This unique instance in Constantin Roman's struggles, and doubts and final triumphs is a poignant example of a dilemma which inevitably confronts the scientist. He is not sure whether the crucial new idea will be easily accepted by his profession, known more for its conservatism, than for its iconoclasm. Therefore he finds it prudent to field these new ideas and test them against new audiences in a series of lectures delivered as a guest speaker of British and Continental universities: Imperial College, Oxford, Cambridge, Norwich, Newcastle, then crossing the English Channel to Liege and Frankfurt (see enclosed list of invited lectures).

There is a somewhat vague code, amongst the scientists, which recognises a claim in a line of research staked out by a colleague - up to a certain point and this very code had been broken, during Roman's time at Cambridge. But when competition comes from more than one quarter there is no holding back and one has to go out and defend one's work, the paternity of which has to be preserved at all costs. This unwritten drama is contained within the pages of the dissertation which we print today which captures with extraordinary ethos the vivid feel of how creative science really happens: Roman's PhD Dissertation is not a history, but an important contribution to the history of Science which some day will be written. Indeed most of its tenets are still valid today, a living proof of how a solid ground is really laid out, for younger generations to build on.

Finally there is the human interest in publishing 25 years on this Dissertation: those of us who ask ourselves "why this publication first written in 1973 should come about in 1998?" must understand the issues to be rather more complex but the motives on the whole more straight forward: in this particular case we deal, at least on a scientific level, with a kind of "restitutio in integrum" of Constantin Roman's work. His contributions published in "Nature" and other prestigious journals were sadly (and for historical reasons) subjected to the "conspiracy of silence" in his native country. This has been our loss, the result of wanton censorship perpetrated by the past regime on the published works of our colleagues in the Diaspora. It is not our intention here to produce an exhaustive inventory of hardships imposed on most Romanian scientists prior to 1989, but this is evidence of our stubborn refusal in accepting them, which is one of the main reasons why we celebrate today Roman's contribution, as we reclaim our memory and welcome him to the fold as one of our own, within our prestigious School of Romanian Geophysicists and Geologists, where he rightfully belongs.

Dr. Şerban Veliciu (Editor)
Scientific Secretary of the Geological Institute of Romania

CREATION

Marin Sorescu

I am writing on earthquake.
If some of my words
Slide too far on
It's the crust of the earth that's to blame
With its lack of stability.

You never know
When a volcano will gape in your desk
And after a day's work
You'll sign straight onto ashes.

Everything metamorphoses
Out of its place.
The lamp from the ceiling comes up to my chin
The mountain from the horizon got into my mouth -
A gag whose fragments
Will be spat out for a long time
By my descendants
To the seventh generation.

The leaves from the tops of the trees
Went into the ground
For fear of earthquakes.

Many of my forefathers
Went into the ground
For fear of earthquakes.

I alone still try to connect
Like railway tracks after derailment
These two lines
Which run one this way
One that way
Amok.

Translated from the Romanian
by
C. Roman and T. Cribb

PREFACE

This work consists of two parts: Part 1 deals with the seismotectonics of the Carpathians and Part 2 with the seismotectonics of Central Asia. There is no apparent correlation between the two regions except the tools of investigation and the claim that the Himalayas are part of the same mountain system as the Carpathians. There are also certain similarities between the seismicity of the Carpathians and that of the Hindu-Kush in Central Asia.

The interest of the Carpathian seismicity lies in the fact that the intermediate depth foci occur under continental crust and that the Benioff zone is confined to a very small subduction zone (60 km horizontal front) and is contained within a vertical parallelepiped. As for Central Asia, the main interest lies in the presence of the world's widest area of shallow seismicity. This study takes into account for each of these areas the geological and geophysical factors (chapters 1 and 5), describes the processing of the seismological information (chapters 2 and 6) and presents physical and geological models for the evolution of the crust (lithosphere) in chapters 3 and 7. The conclusions for each part are presented in chapters 4 and 8 respectively. At the beginning of each of the two parts, that is in chapters 1 and 5 respectively, there is a summary of the seismotectonics of the Carpathians and Central Asia.

The original contribution of Part 1 presents the Carpathian Benioff zone as a vertical parallelepiped

(Roman, 1970) and its subsequent seismotectonic interpretation (Roman, 1971 and 1973c), answering such key questions as the cause of the verticality of the Benioff zone, of its confinement to the elbow of the Carpathian arc, as well as the reason for the intermediate-depth seismicity under continental crust (Roman, 1973b). The original contribution of Part 2 is not so much the computation of a number of focal mechanisms based on the WWSSN readings (Roman, 1973d) as their geotectonic interpretation, in particular the movement of the crust, the geometry of the crustal faults, the relationship between compressional and tensional axes, and the major system of crustal faults which qualify for the status of plate boundaries. Another contribution is made by introducing a quantitative element, that of the seismic magnitude, in addition to the frequency element already used in defining the plate boundaries; this was made possible by devising the relatively simple technique of magnitude screening in half-magnitude classes. This technique led to the definition of a new type of lithospheric plate, the buffer plate (Roman, 1973a). In the Black Sea region, the study of the seismicity led to the definition of yet another type of lithospheric plate, the sub-plate (Roman, 1973b).

Except where specific acknowledgements are made, or reference cited, the work described in this dissertation is original. It is not substantially the same as any that has been, or is being, submitted to any other University and does not exceed 80,000 words in length.

Constantin Roman

ACKNOWLEDGEMENTS

Celor care, in privatiuni si adversitate s-au ocupat de implinirea mea, celor care m-au iubit, m-au educat si au crezut in mine, prietenilor mei din Marea Britanie si de pe continent - toturora adinca recunostiinta.

This work was made possible by the award of a Research Scholarship from Peterhouse, Cambridge (1969-1972), and of numerous travel grants (1969-1973) from the Department of Geodesy and Geophysics, University of Cambridge. In my fourth year of research (1972/1973) I received additional subsistence grants from Peterhouse and the Department of Geophysics and a loan from the University of Cambridge; also my College and University fees were waived to allow me to finish the dissertation. I am most grateful for all of this, and would also like to thank especially my Tutor Dr. Roger Lovatt, the Master and Fellows of Peterhouse and my Professor and Supervisor Sir Edward Bullard.

In my first year, my supervisor was Dr. D.P. McKenzie, who entrusted me with the principle of "publishing as fast as possible", which I have since adopted with great gusto.

I am most indebted to the guidance of Professor Sir Edward Bullard, my supervisor for the last three years, who spared no effort patiently to encourage my work in times of crisis and who has shown an infectious enthusiasm for new ideas and generously gave me a free hand when needed. This resulted in speedy data processing which I carried out in my second year. For this I am also greatly indebted to a number of British and foreign geophysicists who let me use their computing facilities (programs, magnetic tapes with seismological information, computing time) with generous unselfishness. At Blacknest, Dr. H.I.S. Thirlaway gave me access to his program for computing the theoretical P travel-times which were later useful in reading the seismograms; also the Joint Epicentre determination program (JED) and the magnetic tapes with epicentre data from the United States Coast and Geodetic Survey (USCGS). Mr. John Young helped with running these programs. Professor Dr. Hans Berckhemmer, Head of the Department of Geophysics and Meteorology at the Goethe University, Frankfurt/Main, very kindly arranged a visit to his department to study the library of the Worldwide Seismic Stations Network seismograms (WWSSN). This allowed me to compute the focal mechanisms for Central Asia. I am grateful for his hospitality and that of my German colleagues who made my stay at Frankfurt very agreeable and useful.

At Edinburgh Dr. P. Willmore and Dr. E. Arnold kindly offered their computing facilities for processing the focal mechanisms; the programs were run by Mrs. Annette Fluendy, at the International Seismological Centre.

All this invaluable help received at Blacknest, Frankfurt and Edinburgh is gratefully acknowledged.

I am also grateful to the Manager at the I.B.M. Croydon Customer Centre, Mr. Mike Begley, who gave me permission to process my own geophysical data.

The content of the present dissertation was the subject of numerous talks, seminars and colloquia to which I was invited:

1970 - Dept. of Geophysics, Cambridge, and the European Seismological Commission in Luxemburg at its 12th Meeting;

1971 - Depts. of Geophysics and Geology, the Goethe University, Frankfurt/Main and Dept. of Geophysics, Cambridge;

1972 - Dept. of Environmental Sciences, University of East Anglia; United Kingdom Atomic Energy Authority, Blacknest; Dept. of Geodesy and Geophysics, University of Cambridge; Dept. of Geology, University of Cambridge; Dept. of Geology and Dept. of Geophysics, Imperial College, London; Laboratoires de Géophysique et Minéralogie et Pétrologie, Université de Liège;

1973 - Dept. of Geology and Mineralogy, University of Oxford; Dept. of Geophysics, School of Physics, University of Newcastle upon Tyne.

I am grateful to those who asked me to give these talks and organised them for me and to those who, by joining in the discussions, greatly helped me to crystallise the ideas presented in this dissertation.

During the preparation of the papers published (1970, 1971, 1973a, 1973b, 1973c, 1973d) useful criticism was made by Professor Sir Edward Bullard, Dr. D.H. Matthews, Dr. H.I.S. Thirlaway, Dr. W.Q. Limond and Dr. J. Lort. My father helped me to liaise with the editors of geophysical journals in Bucharest and my brother-in-law provided me with useful references from Romanian scientific literature.

Last, but not least, I would like to thank those who patiently and skilfully made my English syntax more acceptable to sensitive ears: a task which I do not envy anyone. I hope the list of names is complete, starting with my supervisor, who was confronted with the crudest version of my text, and continuing through my colleagues in Peterhouse (P. Perry, Esq., D. Daly, Esq., P. Duffet-Smith, Esq., D. Papineau, Esq.), Dr. B. Knights (Selwyn) and T. Cribb, Esq. (Churchill). None of these is a geophysicist (except my supervisor), so by helping me to make my prose palatable I hope they have in turn become more sympathetic to our planet Earth and its rotating lithospheric plates. However, my English must have been so wanting that, despite the interventions of so many skilful natives, Mrs. Dorothy Tanfield (who devoted herself to typing this dissertation) still had more than one sentence to improve. The aesthetic surgery carried out by this conclave of linguistic wizards made the text in the end beyond recognition and consequently my task of proof reading so much more pleasurable. I wish this impression to be shared by my unknown examiners, and by generations to come.

A. introduction

CHAPTER 1

Carpathians

Summary

The revision of earthquake epicentres, focal depths and origin times for 70 Carpathian earthquakes (1928-1965), using Bolt's relocation program, reveals a vertical Benioff zone in the form of a parallelepiped 60 km long, 30 km wide, 160 km deep and oriented N35°E, tangent to the Carpathian arc (Vrancea mountains). The area of shallow focus events is adjacent to the intermediate focus area. Between the 30 km and 60 km depth there is a region of low activity, while between 60 km and 160 km depth there is a region responsible for the present events. Beyond this depth seismicity ends abruptly.

The presence of large masses of andeside , high heat flow, type of basement, crust structure, negative Bouguer anomalies fit the model of a relict piece of lithosphere sinking at a minimum average rate of 1.6 cm/yr under the Carpathian arc very well. This vertical slab is considered to be part of the Black Sea Plate, the boundaries of which correspond roughly to those of the Black Sea basin.

If Bolt's relocation method offers a good basis for interpreting the seismic results in terms of Plate Tectonics theory such is not the case with the P travel time residuals. For the spatial distribution of residuals of all stations for each individual earthquake does not show, as one would expect,

a negative residual anomaly in the azimuth of the slab (N35°E).

A parallel method of relocation has thus been tried (Joint Epicentre Determination, JED) for 58 Carpathian earthquakes from the previous 70. Here the average P travel time residuals of all 58 events at each individual station within a close epicentral distance show a zone of late arrivals (up to +6 seconds) in Hungary, in the area of high heat flow, and early arrivals (-1 second) towards the Black Sea (Crimea).

A two-dimensional model of the evolution of plates is discussed for a period since the Alpine orogenesis and the limitations of the theory as applied to the Carpathian seismotectonics are considered.

1.1 Introduction to the seismotectonic framework

Since the early stages of development of seismology as a modern branch of science, earthquakes in Romania have attracted the attention of such pioneers as Jeffreys, Gutenberg and Richter. This interest stemmed from the existence of a persistent nest of foci, under the continental crust, of the Carpathian arc. Macroseismic observations in Romania have been carried out in observatories since 1893, though spurious information is found as far back as 1716 in "Descriptio Moldaviae", written by Dimitrie Cantemir, the then ruling prince of Moldavia and a Fellow of the Berlin Academy. The old chronicles of Moldavia and Wallachia mention quite a few destructive earthquakes, said to be of bad omen for the ruling prince, who thus ran the risk of being replaced by a rival pretender to the throne. However, some of the earliest seismological evidence, 2500 years ago, comes from the archaeological sites of ancient Greek and Roman cities of Pontus Euxinus (Black Sea) which suffered from earthquakes. The Roman poet Ovid (43 B.C. - 17 A.D.), exiled at Tomis (Constanta), mentioned one of these earthquakes in "Pontica" - would this have been the shock which destroyed the city of Bisone (Cavarna) as suggested by Atanasiu (1961)?

In our study of seismicity we did not make use of historical records. Even for a more recent period, from 1893 to 1928, we found there was not enough information to allow reliable relocations of earthquakes. From the existing Romanian literature on seismology we made use only of the study of isoseismals from Atanasiu's work "Cutremurele de pamint din Romania" (1961). Some focal mechanisms have been published by Constantinescu, Radu, Ritsema and others, but unfortunately the quality of their input data is questionable (see discussion in chapter 2.3). There was also no reliable location of both shallow and intermediate focus events at the Carpathian arc.

It was therefore found necessary to relocate all Carpathian events from 1928 to 1965 using Bolt's and subsequently JED methods (chapter 2.1). A comparative study of these two methods (Bolt and JED) was the object of some very useful geophysical correlations between the P travel time residuals and various anomalies (gravity, heat flow) in the Carpathian area (chapter 2.2). Unfortunately, again the general geophysical information covering Hungary, Romania, Russia and the Black Sea basin is scarce. There is available only a Bouguer anomaly map for Romania and a vaguely qualitative free-air gravity map for the same area. This made it impossible to check our plate model (chapter 3) against any quantitative anomaly profile measured on the field. There are good heat flow results for Hungary, Slovakia, the Soviet Union (Sub-Carpathian flysch, Russian Platform and Crimea) and some parts of the Black Sea, but no published records of heat flow in Romania (not even from bore holes) (see 1.3.2). Some deep seismic soundings have been published whilst others are pending results of current work (1.3.3). There is, on the other hand, a wealth of petrographic, mineralogic and stratigraphic evidence readily available in the Romanian literature. This helped in substantiating the tectonic model proposed for the Carpathians (chapter 3.1).

Our data processing involved some computation carried out in Cambridge and Blacknest using the Bolt and JED relocation programs (see appendix for figures) as well as some minor plotting routines for various types of projections of hypocentres and epicentres on a Calcomp plotter. The input data came from the ISC and BCIS bulletins.

Our work on relocation was published in 'Nature' (1970) and reviewed by the 'New Scientist' (1970). The seismotectonic model for the Carpathians was submitted to and published by the European Seismological Commission in the Proceedings of its XIIth Meeting in Luxemburg (1971). A discussion on seismotectonic boundaries and plate evolution at the Carpathian arc (Roman, 1973b) and a study of P travel-time residuals for the same (Roman, 1973c) have just been published. A series of talks on the same subject was delivered at colloquia in various Universities, during the period 1969-1972: Geophysics, Cambridge (1970 and 1972); Geophysics, Frankfurt (1971); UKAEA (1972); Geophysics, East Anglia (1972); Geology, Cambridge (1972); Université de Liège, Belgium (1972) and Department of Geology, Oxford (1973). Together with private consultations in the Department of Geophysics at Cambridge they proved to be of great help in shaping the present views on seismotectonics in the Carpathians and its interpretation in terms of plate tectonics.

1.2 Introduction to the Carpathian Geology

The main units of the Carpathian system are: (1) Eastern Carpathians, (2) Southern Carpathians, (3) Western Carpathians or the Transylvanian Alps, (4) Transylvanian Basin, (5) Panonian Basin; external to the mountain arc are: (6) Russian Platform, (7) Gaetic Basin, and (8) Black Sea Basin (fig. 1-1).

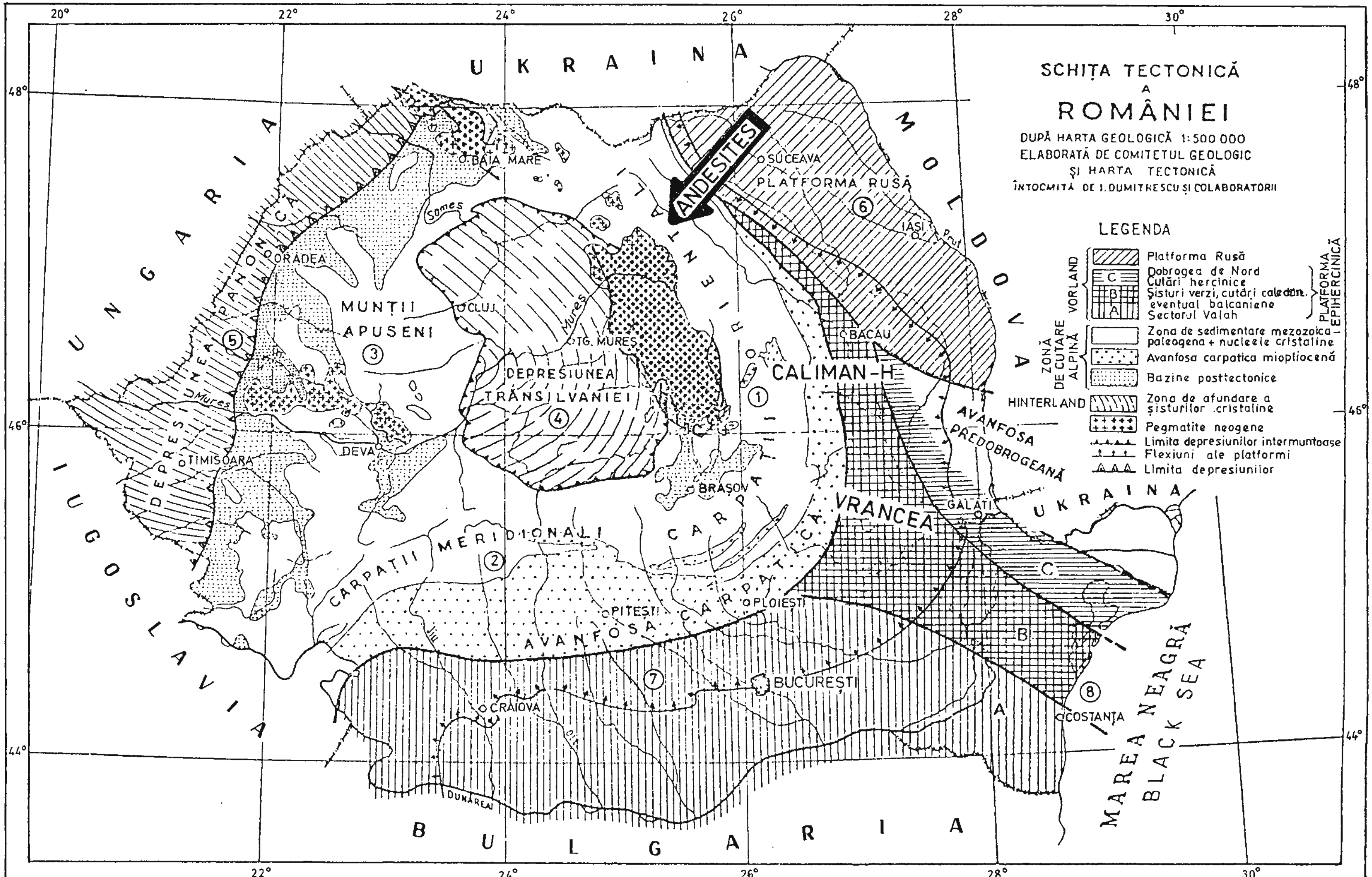
(1) Eastern Carpathians: these form a sharp bend of 90° in the zone of the Vrancea mountains, before linking with the Southern Carpathians. The interest of Vrancea resides in the presence of the persistent nest of intermediate focus events, which form the subject of our seismic investigations.

The Eastern Carpathians have two interesting characteristics: first a parallel geologic sequence, from west to east - the crystalline zone, the flysch zone and the Neogene zone. This sequence indicates the passage from the older Mesozoic formations to the younger ones from the Neogene

Fig. 1-1

Tectonic map of Romania (after Socolescu & Esca, 1966).

(1) Eastern Carpathians (including the zone of subcrustal seismicity under the Vrancea mountains, solid circle, and the Caliman-Harghita mountains of Neogene andesitic rocks); (2) Southern Carpathians; (3) Western Carpathians (or the Transylvanian Alps, or the Apuseni mountains); (4) Transylvanian basin; (5) Pannonian basin; (6) Russian platform; (7) Gaetic basin (between the Southern Carpathians and the Balkans); (8) Black Sea basin. The above numbers correspond to the subdivisions in the text.


SCHIȚA TECTONICĂ
A
ROMÂNIEI
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ELABORATĂ DE COMITETUL GEOLOGIC
ȘI HARTA TECTONICĂ
ÎNTOCMITĂ DE I. DUMITRESCU ȘI COLABORATORII
LEGENDA
VORLAND
Platforma Rusă
Dobrogea de Nord
Cutări hercinice
Șisturi verzi, cutări caledon. eventual balcaniene
Sectorul Valah
PLATFORMA EPIHERCINICĂ
ZONĂ DE CUTARE ALPINĂ
Zona de sedimentare mezozoica - paleogena + nucleele cristaline
Avanfosa carpatica mioplіocenă
Bazine posttectonice
HINTERLAND
Zona de afundare a șisturilor cristaline
Pegmatite neogene
Limita depresiunilor intermuntoase
Flexiuni ale platformi
Limita depresiunilor
UKRAINA
MOLDOVA
UNGARIA
IUGOSLAVIA
BULGARIA
MAREA NEAGRĂ
BLACK SEA
ANDESITES
PLATFORMA RUSĂ
SUCEAVA
IAȘI
Prut
BACAU
CALIMAN-H
VRANCEA
AVANFOSA PREDOBROGEANĂ
GALAȚI
CONSTANȚA
BUCUREȘTI
PLOIEȘTI
PITEȘTI
CRAIOVA
DUNĂREA
AVANFOSA CARPATICĂ
CARPAȚII MERIDIONALI
CARPAȚII
BRAȘOV
DEPRESIUNEA TRANSILVANIEI
TG. MUREȘ
Mureș
CLUJ
MUNȚII APUSENI
BAIA MARE
Someș
ORADEA
DEVA
TIMIȘOARA
DEPRESIUNEA PANONICĂ
20°
22°
24°
26°
28°
30°
44°
46°
48°
Fig. 1 - 1

and at the same time shows that the axis of the Carpathian geosyncline, where these deposits were formed, gradually migrated eastward. (fig.1-3).

A second important characteristic of the Eastern Carpathians is the presence of the large Caliman-Harghita volcanic range. The volcanoes are mainly andesitic, with the odd rhyolites, dacites and basalts, and are known to have erupted during Neogene times.(figs.1-1,1-3,1-30).

(2) The Southern Carpathians are formed by a crystalline zone, which is autochtonous and is overthrust from the south by schists (the Gaetic overthrust).

(3) The Transylvanian Alps also present a crystalline zone. Older volcanics are of Triassic-Cretaceous age (230-70 m.y.) and younger acid volcanics are of Neogene age (25 m.y.).

The geological evidence (Macovei, 1958; Oncescu, 1959) shows that during the whole of Tertiary times (70 - 1 m.y.) the Carpathian system was an island arc.(fig.1-7).

(4) The Transylvanian Basin, having the Caliman-Harghita volcanic range to the east and the Transylvanian Alps to the west, was formed through subsidence during the Upper Cretaceous (70 m.y.) giving way to an internal sea. The Transylvanian basin has important salt and methane gas deposits.

(5) The Panonian Basin to the east of the Transylvanian Alps was, like the Transylvanian basin, an internal sea during the Cretaceous and Tertiary. One therefore finds the same geological history for both. The deep seismic sounding

(Sollogub, 1969) shows a similar basement structure for both the Panonian and Transylvanian basins. Yanshin (1966) considers this basement of Alpine tectonic age(figs.1-5,-13,-22).

(6) The Russian Platform borders the Eastern Carpathians to the east and the Black Sea basin to the north. During the whole period of the Alpine (Carpathian) orogenesis the basement was not active, since it was formed by crystalline schists of Pre-Cambrian age (Oncescu, 1959). According to Yanshin (1966) the last tectonic movements which affected the platform happened during the Hercynian orogenesis, to which the Urals and part of the Crimean mountains belong.

(7) The Gaetic Basin is contained between the Southern Carpathians and the Balkans. The basement of the Gaetic basin belongs to the same unit as the Russian platform (Hercynian) (Yanshin, 1966) and is overlain by thick Mesozoic, Neogene and Quaternary sediments (Oncescu, 1959).

(8) The Black Sea Basin is a remnant of the old Tethys sea and has all the characteristics of the internal seas, as described by Menard (1967). During Cretaceous times the Tethys sea covered the Gaetic basin, precisely during the period when the Carpathian mountains were an island arc and the Cretaceous seas from Western Europe transgressed the Panonian and Transylvanian basihs, behind the island arc.(figs.1-7,-32).

The Black Sea presents partly an oceanic crust to the south and partly an intermediate type of crust to the north (towards the Crimean), showing a transition from the oceanic to the continental type of crust (Sollogub, 1969; Kosminskaya et al., 1969).

1.2.1 Dynamics of the Carpathians

Certainly the most accurate account of the tectonics of the Carpathians and adjoining areas would come from deep seismic soundings, the results of which have been commented on by Constantinescu et al. (1972) and Enescu et al. (1972) and will be discussed in detail in chapter 1.3.3.

There are a number of gravity surveys (Constantinescu et al., 1967; Socolescu et al., 1964; Petrescu and Radu, 1965) showing major crustal displacements in Romania, but the quality of the interpretation has been proved to be less reliable since the deep seismic sounding (Constantinescu et al., 1972; Enescu et al., 1972).

There is a very interesting survey of the vertical movement in Romania showing at the Carpathian arc, over the area known to have the thickest packet of sediments (18 km at Focsani), a zone of subsidence with a sinking rate of 1 mm/yr. This zone is external to the Carpathian arc and follows the (fig.1-2) trend of the mountain elbow. Other areas in the South Carpathians produce an uplift up to 2-3 mm/yr. These figures have been obtained through repeated land surveys by Ciocârdel et al. (1968). It is striking that this zone of subsidence is confined to the Carpathian elbow instead of following all along the mountain arc; it does in fact correspond to a cuvette in the Moho (Constantinescu et al., 1972) and is no doubt linked with the nest of intermediate depth foci at the Carpathian arc,

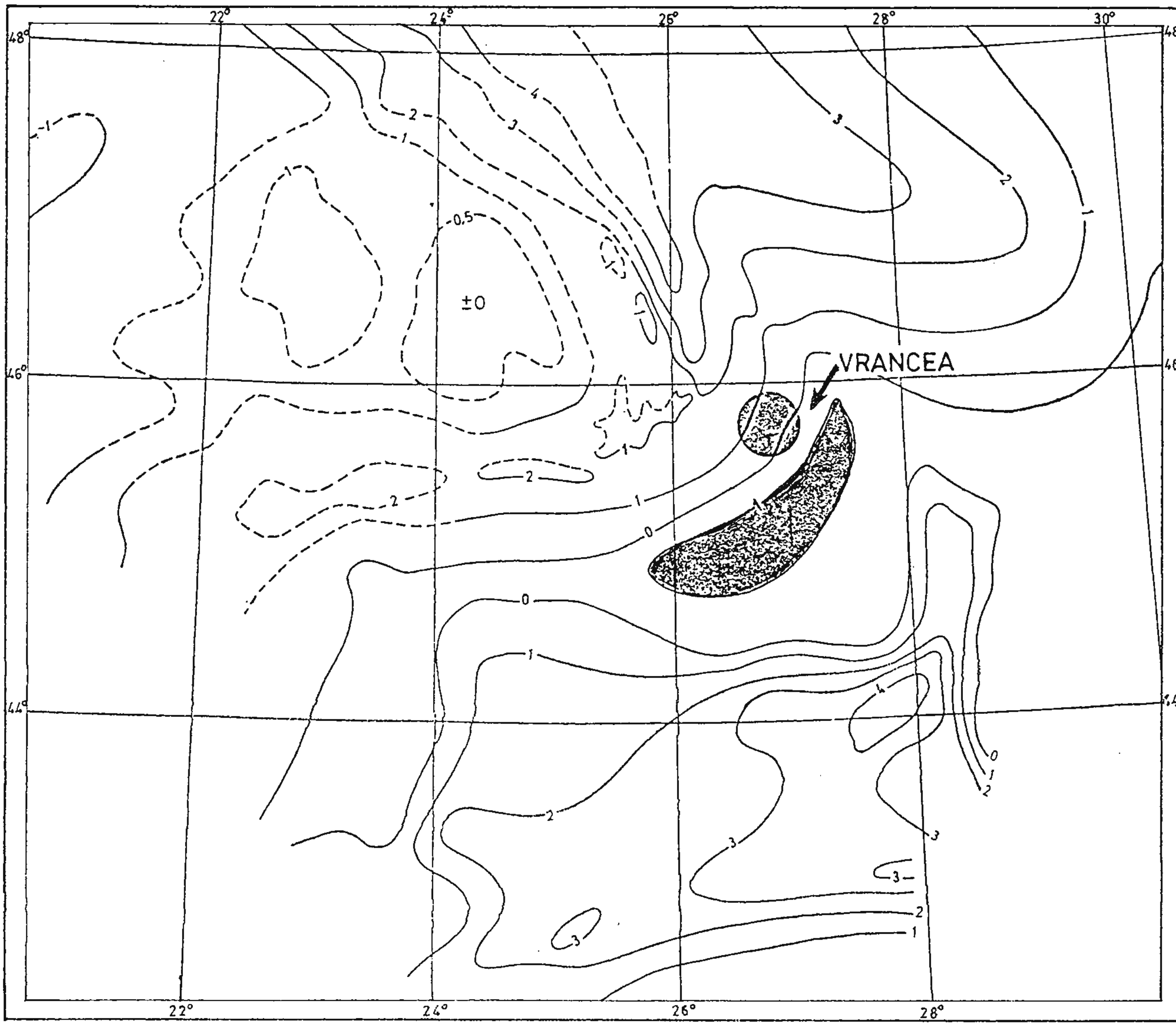


Fig.1-2

<u>Vertical movement at the Carpathian arc</u> (after <u>Ciocârdel</u> & al.,1972): as it appears from repeated survey.
The subcrustal foci are represented by a solid circle.
The isocathabasis (lines of equal uplift/depression) are in mm/yr. It is noticeable that at the Carpathian arc in the region identified with the zone of lithospheric underthrust responsible for the subcrustal foci, there is a trough with a depression rate of 1 mm/yr (shaded area). This trough also corresponds to a cuvette formation in the Moho, recently evidenced by the deep seismic sounding.

being the very region which accumulates, through the gravitational force, the sediments of the continental crust which is pulled by the sinking lithosphere under the mountain elbow - this accounts for the 18 km thick packet of sediments. Ciocârdel and Socolescu (1971) discuss the geometry of the crustal faults in that region and show that the fractures are parallel to the tangent of the Carpathian arc. Ciocârdel et al. (1970) suggest that the cuvette external to the Carpathian arc is tectonically lined with a subduction zone along the southern sub-Carpathians and in an eastward direction with the region north of the Crimea and the Caucasus. These authors also suggest that the 2 mm pa uplift of the Southern Carpathian is due to the push from the Adriatic. If such is the case, then this movement must be relatively recent, i.e. when the Adriatic started to close up some 5 my ago and the South Carpathian uplift was at its maximum rate.

An even more intriguing correlation could be found between the megatectonic movement caused in the western Mediterranean by the opening of the Atlantic and its possible consequence in the eastern Mediterranean basin and the Carpathians. If the opening of the Atlantic has coincided with the closing up of the Tethys, then it would be normal that since Jurassic times, some 180 my ago, the floor of the Tethys must have been consumed somewhere and that there should be some geological evidence for it (Smith, 1971). Probably such a front along which the oceanic floor was consumed was also the Southern Carpathians; Ciocârdel and Socolescu (1969) found lower Jurassic deposits of serpentinites and basic tuffs, the former being the end product of a geochemical process known as the serpentinization of the basic rocks which once formed the oceanic floor. These, together with the ophiolites and the diabase found by Codarcea (quoted by Ciocârdel and Socolescu, 1969), seem to support Smith's interpretation (1971). Other basic formations in the Southern Carpathians, according to Ciocârdel and Socolescu (1969), have been transformed into amphibolites and micaschists.

Large masses of pillow lavas (diabase, porphyrites, melaphyres) in the Mures Mountains, within the range of the Transylvanian Alps, are typical of the oceanic floor of post-Triassic age (younger than 180 my) and are similar to the formations of the Sumadja Mountains in Yugoslavia; apparently during the post-Triassic - middle Cretaceous period (180-100 my ago) the Mures Mountains were carried some 100 miles away into their present position. This event, involving huge compressional forces associated with the destruction of the oceanic floor, links the tectonics of Transylvania and the Southern Carpathians with the anticlockwise movement of Italy and its corollary, the closure of the Adriatic.

If we are satisfied that the Southern Carpathians and the Transylvanian Alps bear sufficient geological evidence to account for the closure of Tethys and that their structure is closely enough linked with the evolution of the central and eastern Mediterranean, this does still not explain the dynamics of the Eastern Carpathians and the presence of the subcrustal nest of earthquakes under its arc (in the region of the Vrancea Mountains).(fig.1-15).

It is a fact that the history of the Eastern and Southern Carpathians is different and that they developed in different stages. Without taking into account the tectonic movement, this difference is apparent from the age of the flysch and the molasses, which suggest the delay between the orogeny of the Southern Carpathians and that of the Eastern Carpathians. Take for example the molasses which are younger (of Neogene age; 25 my) in the Eastern Carpathians than in the Southern Carpathians (of Paleogene and Neogene age; 70 my). The flysch likewise is younger in the Eastern Carpathians (Cretaceous + Paleogene; 130-25 my) than in the Southern Carpathians and the Transylvanian Alps (Cretaceous, 130-70 my) (Ianovici et al., 1966). This would also imply that the period during which the compressional forces acted varied from the eastern branch to the southern branch of the Carpathians and also that the life span of the oceanic trench external to the Carpathian arc differed when these mountains were an island arc. All this evidence leads us to believe that the oceanic trench and its subduction zone (e.g. sinking lithosphere) lasted until more recent times along the Eastern Carpathians than along the Southern Carpathians. This image fits the distribution of the acid Neogene volcanism, which exists within the Eastern Carpathian branch alone and not within the Southern Carpathians. This point also helps to clarify the reasons why there is no subcrustal seismic activity at all along the Southern Carpathians, but only under the Vrancea Mountains which are part of the Eastern Carpathians.

The reason why this nest of subcrustal foci is confined to only a small area (Roman, 1970) at the southern end of the Eastern Carpathian chain can be explained very easily in geological terms: as it appears that the Neogene volcanism in the Eastern Carpathians is much younger in the south than in the north, it results that the oceanic trench external to these mountains first closed to the north and then to the south. Knowing that the thermal gradient of the sinking lithosphere could not last longer than for 10 my, this means that the sinking lithosphere disappeared first in the north, whilst under Vrancea in the south this thermal gradient still exists in the region of the subcrustal events.(fig.1-35 and chapter 3-2).

There is no doubt that a trench once existed along the Eastern Carpathian mountains: Bancila (1967) shows in a cross section the eastward overthrust of the Eastern Carpathians in (fig.1-3 the direction of the Russian platform. The movement between two adjoining tectonic blocs being relative, it is difficult to say whether the geometry of the Eastern Carpathians is due to the forces coming from the Transylvanian basement to the west or from the action of the Russian platform to the east. Ciocârdel and Socolescu (1969) speak of a clockwise rotation of Transylvania with respect to the Russian platform, and the same authors (1972) later mention a westward drift of the Russian platform which accounts for the overthrust of the Eastern Carpathian sedimentary over the platform; this image fits our model well for the feeding of the Eastern Carpathian trench from the east and the gradual closure of this arm of the sea (probably during the Miocene times - Macovei, 1958). (figs.1-32 and 1-35).

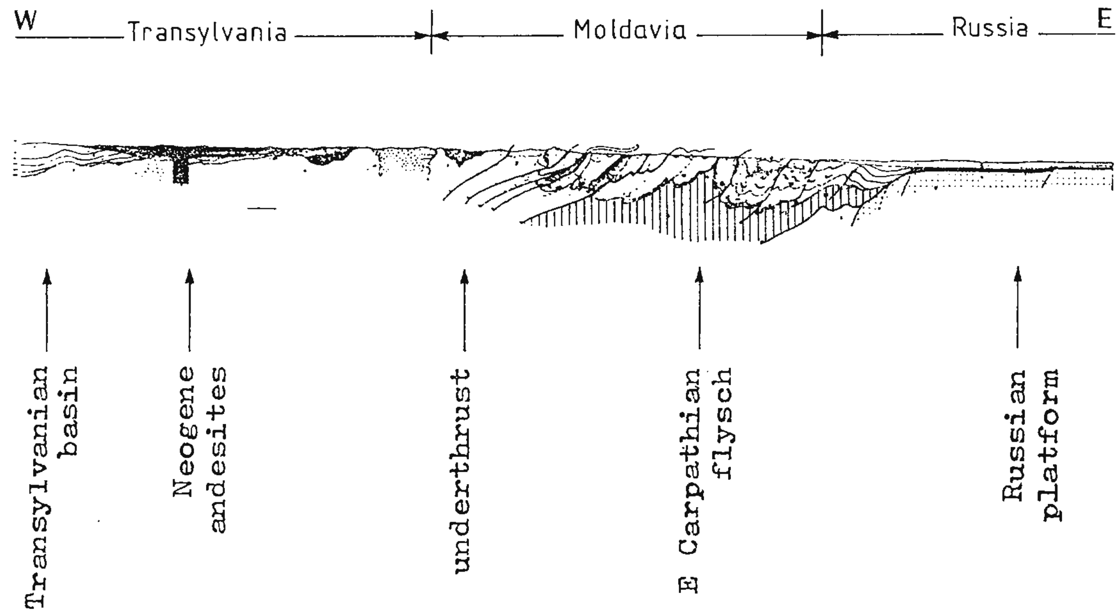


Fig. 1-3

Eastern Carpathians, a vertical cross-section (after Bancila, 1967). To the west, that is on the Transylvanian slope of the E Carpathians, there are the Neogene igneous rocks. The structure of the folding in an easterly direction, towards the Russian platform, suggests that the Carpathian island arc was underthrust from the east, during Miocene times, producing the volcanic activity to the west, on the Transylvanian side of the E Carpathians.

Ciocârdel and Socolescu also mention a major wrench fault along the Southern Carpathians extending eastward towards the Black Sea and westward towards the Alpine mountains of Albania (Skutari). This line corresponds to an isostatic "high" to the north and an isostatic "low" to the south, which explains the uplift of the Southern Carpathians continuing today.

Crustal fractures connected to the Carpathian mountain system. One of the major crustal fractures along the Eastern Carpathian mountains crosses the zone of Vrancea, where the subcrustal foci are, reaching the Danube valley further to the south, and the territory of Bulgaria, where it is known as the Tvardica fracture. According to Ciocârdel and Socolescu (1969), this crustal fault is part of a 1,700 km front linking the Karawanken Mountains to the Tvardica fault. It is difficult to assess the relationship between this crustal fracture and the seismicity of the Vrancea Mountains, but one can say, however, with certainty that this fault is no longer active, as it is not known to produce any important shocks (Atanasiu, 1961).

The Capidava-Canara fracture (fig.1-4,5), known from gravity surveys (Socolescu et al., 1967; Constantinescu et al., 1967) in Central Dobrogea, is another important crustal fracture which is the product of the Cymmerian diastrophysm (180-130 my ago, contemporary with the opening of the Atlantic) (Ianovici et al., 1966). This fault line probably extends eastward across the Black Sea basin towards the Crimea and further east to the Caucasus, separating the Hercynian from the Alpine

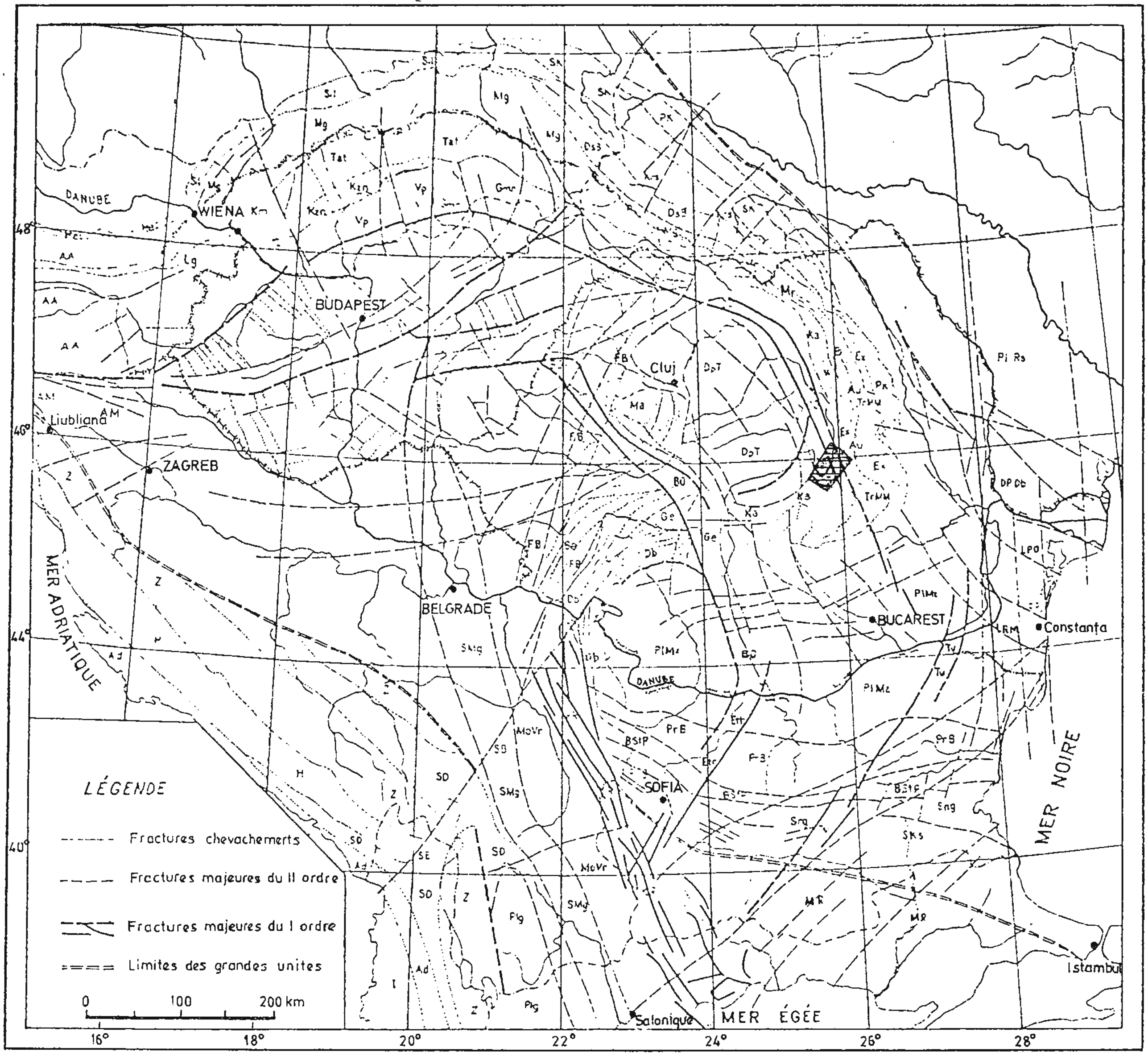


Fig.1-4

Major crustal fractures in south-eastern Europe (after Ciocârdel & Socolescu, 1969). The shaded area at the Carpathian arc is the zone of subcrustal seismicity. The crustal fractures we are referring to in this text are: 'Tv'-Tvardica fracture in Bulgaria; 'PC'-Peceneaga-Camena fracture in northern Dobrogea, between the Danube and the Black Sea; 'CC'-Capidava-Canara fracture in southern Dobrogea.

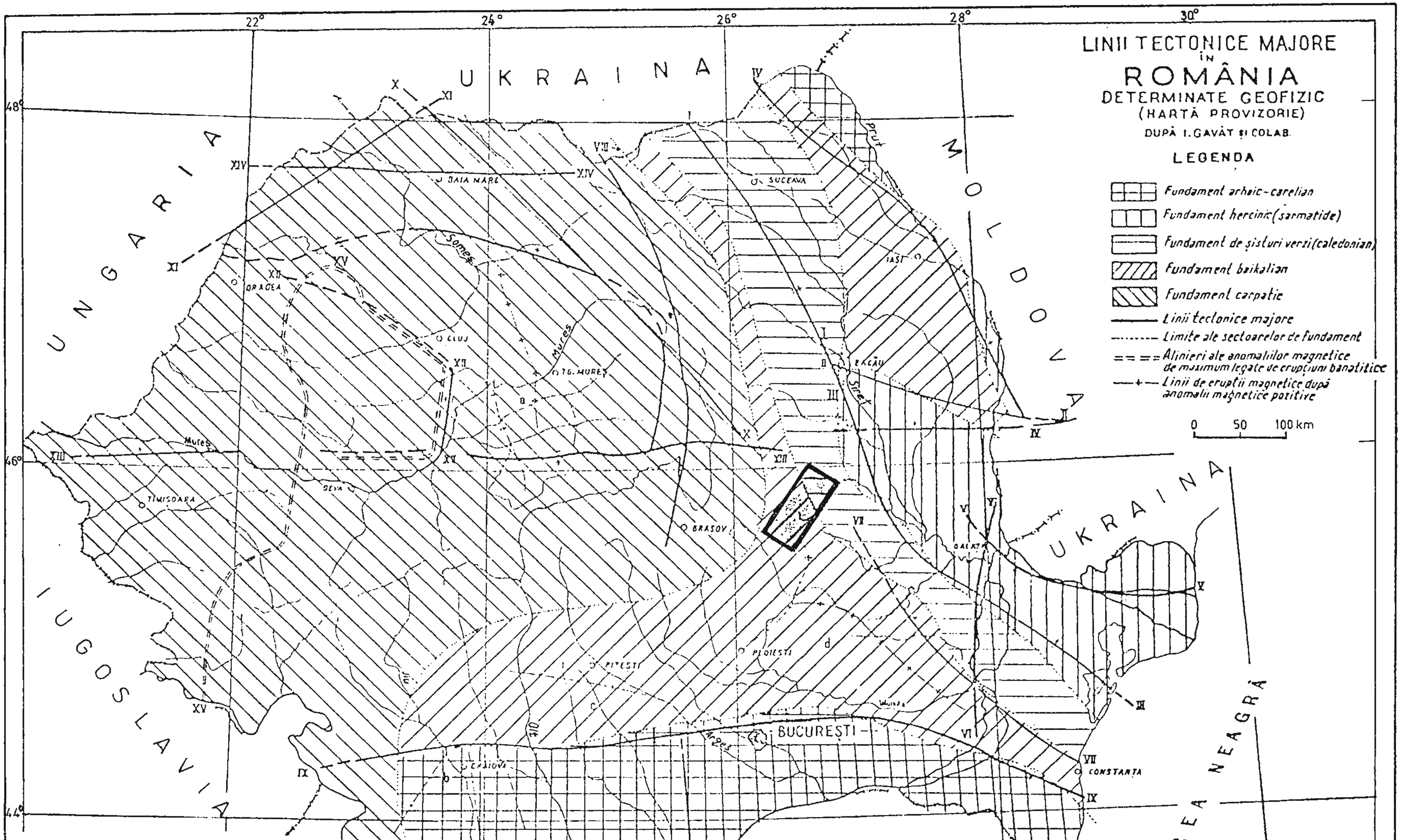


Fig.1-5

Major basement units of Romania (after Ciocârdel & Esca, 1966). The shaded rectangle marks the zone of lithospheric underthrust under the Vrancea mountains, as defined by the relocation of the Carpathian epicentres.

orogenesis. To the west the Capidava-Canara fault appears to be linked with the Carpathian arc, as it results from the deep seismic sounding of Enescu et al. (1972); the geometry of the fault line suggests that the southern bloc underthrust the northern bloc. There are a number of historic earthquakes in Dobrogea, some of which may have occurred along this fracture line, but this fact can be established only with certainty by a microseismic study. Only three destructive earthquakes with epicentres in Dobrogea are known in historic times: in the 1st century B.C. - which destroyed the city of Bisone; in 543 - which destroyed the city of Dyonisopolis (Balcic) and more recently on 31 March 1901; but their epicentres must have been further south from the Capidava-Canara fracture, judging at least from the position of the most modern event of the three.

The wrench fault along the Southern Carpathians is again difficult to assess as to its seismic activity, because of the poor quality of the local seismic network. The seismic station in Romania had mechanical seismographs until 1956, only capable of detecting events of magnitude larger than 2.7 (m_B) (Radu and Tobyas, 1965 and 1968). Since 1956 the introduction of electromagnetic seismographs did not improve the detection capability. Airinei (1966), Petrescu et al. (1965) and Atanasiu (1961) review the seismic activity linked with the active faults of the southern sub-Carpathians, and yet again only a complete microseismic study can assess which faults are active and which are not, and what tectonic significance they might have on a regional scale.

To conclude, the only active crustal faults in Romania are situated at the Carpathian elbow and are intimately connected with the zone of intermediate depth earthquakes. During the past tectonic history other major crustal faults may have been seismically active, but they no longer are today, their presence being revealed merely by gravity or DSS surveys. However, the geometry of folding coupled with petrologic observation is capable of yielding information as to the evolution of the zone of subsidence at the Carpathian elbow, suggestive of a relict piece of lithosphere now under continental crust.

1.2.2 Mineralogic and petrographic evidence

The Molasse fills the various intra-Carpathian basins (Panonian, Transylvanian basins) and the avantfosse. In the Eastern Carpathians the molasse is of Neogene age (25-1 my), whilst in the Southern Carpathians and the Transylvanian Alps the age is Paleogene and Neogene (70-1 my). Deposits of evaporites (salt, gypsum) and coal are typical of the Carpathian molasse (Ianovici et al., 1966).

The Flysch has mainly Cretaceous deposits (in the Eastern Carpathians it has also Neogene deposits). In the Eastern Carpathians the flysch is of geosyncline type, whilst in the Transylvanian Alps it is of an eugeosyncline type, starting with a basic volcanism (diabase, porphyrites).

Ophiolites of Mesozoic age are apparent in the Transylvanian Alps (Metaliferi, Trascau mountains) and the Southern Carpathians (Cerna, Mehedinti, Vulcan, Paring mountains). Both ophiolitic ranges are connected with ferrous and manganese ore deposits. In the Eastern Carpathians ophiolites are to be found in the Haghimas and Rarau mountains.

The Volcanic formations present two stages:

(1) from the Upper Cretaceous to the Paleocene (100-60 my), corresponding to the sub-Hercynian and Laramide phases; such volcanics are present in the Transylvanian Alps and the Southern Carpathians and they are intrusive rocks (granodiorites, diorites), dykes (porphires, andesites, lamprophires) and extrusive rocks (tuffs, agglomerates).

(2) The Neogene (25-1 my) volcanism is almost exclusively confined to the Caliman-Harghita mountains in the Eastern Carpathians and contains andesites, dacites, rhyolites and some basalts and pyroclastics.(fig.1-30).

The study of volcanism gives at least two clues to the interpretation of Plate Tectonics activity: one refers to the temperature, pressure and depth corresponding to the formation of certain types of rocks; a second clue is given in conjunction with radiometric age determination as to what phase of tectonism such volcanics belong.

Lipman et al. (1972), discussing the Cenozoic volcanism in the Western United States, conclude that there are typical associations between Lower and Middle Cenozoic volcanic fields and plate convergence. Lavas are typically andesites, dacites, rhyodacites, just as there are in the Eastern Carpathians (Ianovici et al., 1966). Hypabissal intrusive rocks are granodiorites, monzonites and quartz-monzonites, which, again, exist in the Transylvanian Alps and the Southern Carpathians.

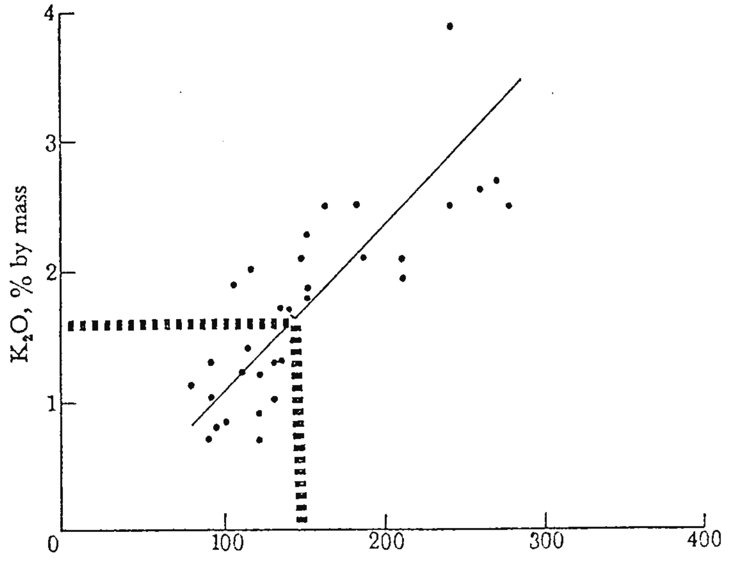


Fig.1-6

<u>The alkalic content of volcanoes above the Benioff zone</u> (after <u>Lipman et al.</u>,1971). In the case of the Eastern Carpathian Neogene volcanism the K_2O content (at 60% SiO_2) is of 1.6%, which would require a 160 km depth for the Benioff zone; this is in agreement with the Vrancea seismicity. The values for the Carpathians are marked in shaded thick line. <u>Kuno</u> (1965) however postulates a 200 km depth necessary for the formation of andesites.

The same authors interpret the presence of ash flow tuffs and low silica rhyolites as high-level differentiates of intermediate composition magmas. Again, tuffs and rhyolites are present in the Carpathians (Ianovici et al., 1966).

It is known that, in the circum-Pacific regions of active subduction-related volcanism, the K_2O-SiO_2 ratios of andesitic rocks increase systematically with increasing depth of the Benioff zone that marks the subduction boundary (Dickinson and Hatherton, 1967; Hatherton and Dickinson, 1969). In the case of the Carpathians this K_2O-SiO_2 ratio could prove a useful method in establishing the depth and shape of the Middle Cenozoic subduction system. Atanasiu (1958), in his study of the Neogene in Romania, quotes a 1.39% (1.41%) K_2O for a 53.53% (52.60%) SiO_2 content for the basaltic andesites of Calimani mountains; this alkalic percentage would be some 1.55% (1.60%) to 60.0% SiO_2. If one compares this alkalic content of the Carpathians with the one of the andesites of the United States by using the least square best fit line suggested by Hatherton and Dickinson (1969), then the inferred depth of the Benioff zone under the volcanoes would be approximately 160 km (fig. 1-6). It may be plausible to suggest though that the active seismic Benioff zone of Vrancea mountains (E. Carpathians), which is today contained on a 60 km front, was at one time following the entire Carpathian arc, when the mountains were a Cenozoic island arc (fig. 1-7). At least the presence of large masses of andesites within the Eastern Carpathians, from the Vrancea mountains to Slovakia, are a proof of a former subduction zone, active all along the

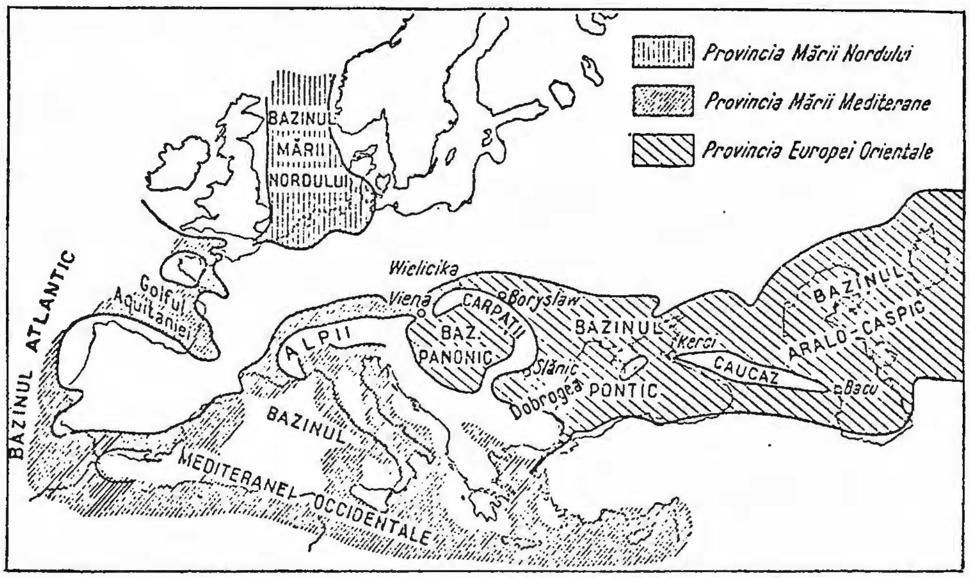


Fig.1-7

Palaeogeographic map of Europe during the Miocene (after Macovei,1958). The Carpathians are an island arc and judging from the presence of the Neogene andesites, an active trench stretched from Slovakia, through southern Poland to the Vrancea mountains. The Pannonian and Transylvanian basins were an internal sea behind the Carpathian island arc.

arc during the Tertiary and now confined to the 60 km front of underthrust tangent to the Vrancea arc.

According to Kuno (1965), andesites are formed at a depth of at least 200 km, which implies that, during the Neogene volcanic activity, the Carpathian subduction zone was much more important than it appears to be today. From the point of view of plate tectonics, this has major implications, as it means that the Benioff zone was deeper than the present 160 km, the heat transfer more important, the sinking rate more rapid than the present minimum average of 1.6 cm/yr and consequently the seismicity more active, i.e. a larger number of earthquakes of a greater magnitude (Roman, 1971).

As for the implications of mineral analysis, it appears that a detailed study of olivines would give information on the direction of stress (Sugimura and Uyeda, 1967). The olivines from the Muresau region, in the Eastern Carpathians, could possibly throw light on the build up of stress through plates movement (Roman, 1971).

1.3 Introduction to the geophysical aspects of the Carpathians

The structure of the earth's crust in Romania was the subject of a few gravity studies whose interpretation was presented by Botezatu (1959), Socolescu et al. (1964), Petrescu and Radu (1965) and Airinei (1966). Constantinescu et al. (1967) correlated the gravity and seismological observations in an attempt to put constraints on to the gravity model of the earth's crust. These measurements and their interpretation proved of little value for two reasons:

first, the deep seismic sounding carried out on the territory of Romania gave absolute values for the Conrad and Moho discontinuities which contradicted the results of the gravity interpretation: this proved that the gravity model was wrong; secondly, the map of the freeair gravity anomalies for Romania, on which the model was based, was never made available to allow us to make our own model, particularly at the Carpathian arc, known for its thick packet of sediments and lithospheric underthrust (Roman, 1970 and 1971).(fig.1-11).

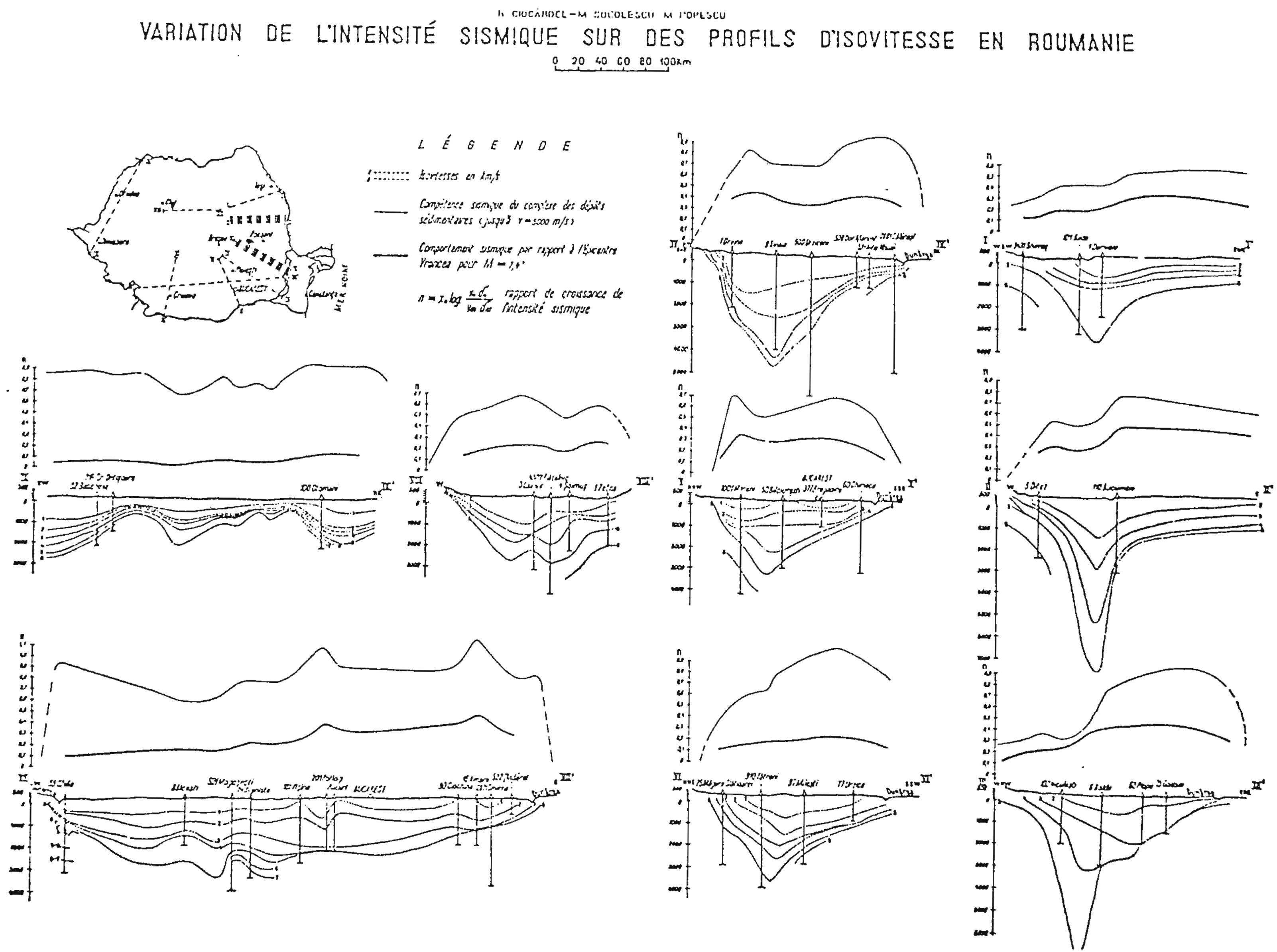
There are no direct measurements of heat flow on the Romanian territory, but these values can be extrapolated by considering similar geological units (Alpine orogeny foredeeps, platforms) from the neighbouring countries, where such information is available (Boldizsàr (1964) for Hungary; Boldizsàr (1965) for Slovakia; Boldizsàr (1968) for the Vienna basin; Sologub and Mihailova (1969) for the Ukraine, Crimea and the Caucasus; Lee and Uyeda (1965) for the Black Sea basin and the Caucasus).

So far only studies are available for the post-volcanic activity in the Carpathians involving temperatures of thermal springs either at the surface, or well logging, ranging from 18°C to 40.5°C in the Eastern Carpathians (Airinei and Pricajan, 1972a,b). These data should be treated with utmost caution as they may not be directly linked with a high heat flow behind the Carpathian arc, but merely with the effect at the surface of the exothermic changes due to the Neogene volcanism, now extinct.

An attempt to correlate the model of a lithospheric

Fig.1-8

<u>Isovelocity profiles across the Carpathians</u> (after <u>Ciocârdel</u> et al.,1972). Profiles II and III are the most interesting as they respectively cross to the north and to the south of the Vrancea mountains. The shaded area shows the anomaly of the 6.0 km/second isovelocity which corresponds to a zone of maximum seismic intensity, over the thickest packet of sediments in the sub-Carpathians. This anomalous area is external to the zone of lithospheric underthrust and it corresponds to the area of depression (fig.1-2) and also to a 'cuvette' in the Moho, recently evidenced by the DSS.



VARIATION DE L'INTENSITÉ SISMIQUE SUR DES PROFILS D'ISOVITESSE EN ROUMANIE
0 20 40 60 80 100km
LÉGENDE
Vitesses en km/s
Comportement sismique du complexe des dépôts sédimentaires (jusqu'à v = 5000 m/s)
Comportement sismique par rapport à l'Epicentre Vrancea pour M = 7,4
rapport de croissance de l'intensité sismique
MER NOIRE

Fig. 1-8

underthrust at the Carpathian arc, and its consequence the high heat flow from the Transylvanian, Panonian and Vienna basins, made by Roman (1971), showed that such a high heat flow as measured in Hungary can be generated by a 160 km depth of lithosphere under the Carpathian arc of Romania.

The deep seismic sounding was carried out only recently along a most important profile oriented ESE-WNW from the Black Sea basin across the Carpathian arc in the zone of the Vrancea mountains right through Transylvania to the Panonian basin; another profile NNE-SSW is at a right angle to the previous DSS profile, which it crosses at Galati, near the Danube, and crosses a Hercynian basement covered with a thick layer of sediments. Finally, explosion in the Panonian basin in Hungary along the profile III allowed the evaluation of the Moho and Conrad subsurface in the NW region of Transylvania(fig.1-12).

The specific values obtained by the DSS in Romania will be discussed in detail in chapter 1.3.3. What one could comment on at this stage is that the values for the Moho obtained by Enescu et al. (1972) under the Carpathian arc, of 50-55 km depth, are comparable with the ones presented by Sologub (1969) for the Carpathians and by Closs (1969) for the Western Alps. Also it may be worthwhile pointing out that the structure of the crust as revealed by DSS in the Black Sea and the Panonian basins shows the same values; without having such information, and based solely on the comparative Bouguer anomaly map for SE Europe, I suggested (Roman, 1970 and 1971) that the structures of the crust in these basins should be the same, as they underwent a similar history with a more pronounced

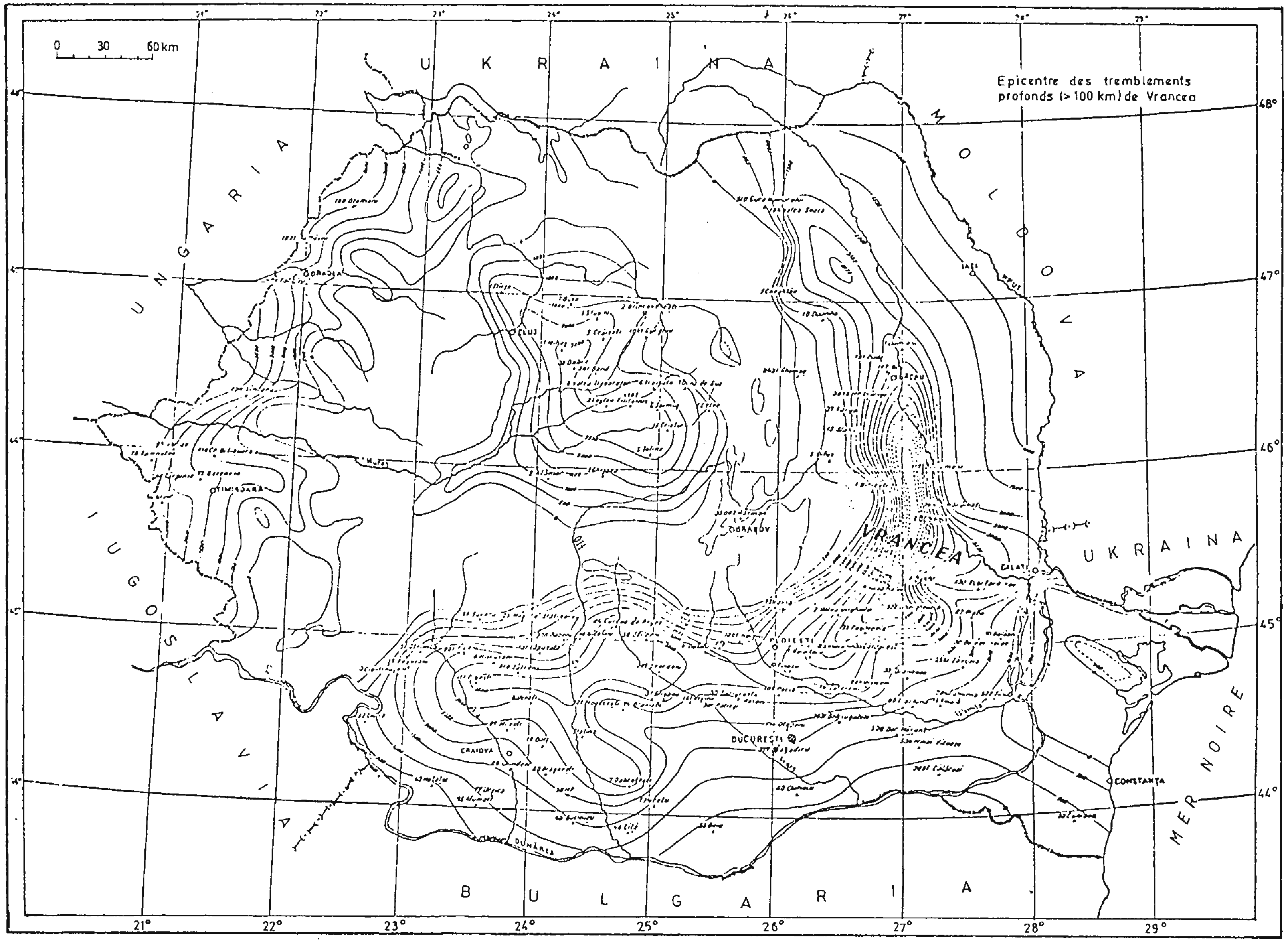


Fig.1-9

Map of isovelocity (5 km/second longitudinal waves from seismic logging) (after Ciocârdel et al.,1972). This map shows the variation with depth of the isovelocity: the anomaly adjacent to the Vrancea epicentral zone corresponds with the thickest packet of sediments at the sub-Carpathian arc.

Fig.1-10

Bouguer anomaly map of Romania (after Ciocârdel & Esca, 1966):
The negative Bouguer anomaly is found external to the Carpathian arc and also to the Vrancea (solid circle). The positive Bouguer anomalies from the Dobrogea and the Pannonian basin regions (arrows), being comparable in intensity are suggestive of a comparable crustal structure.

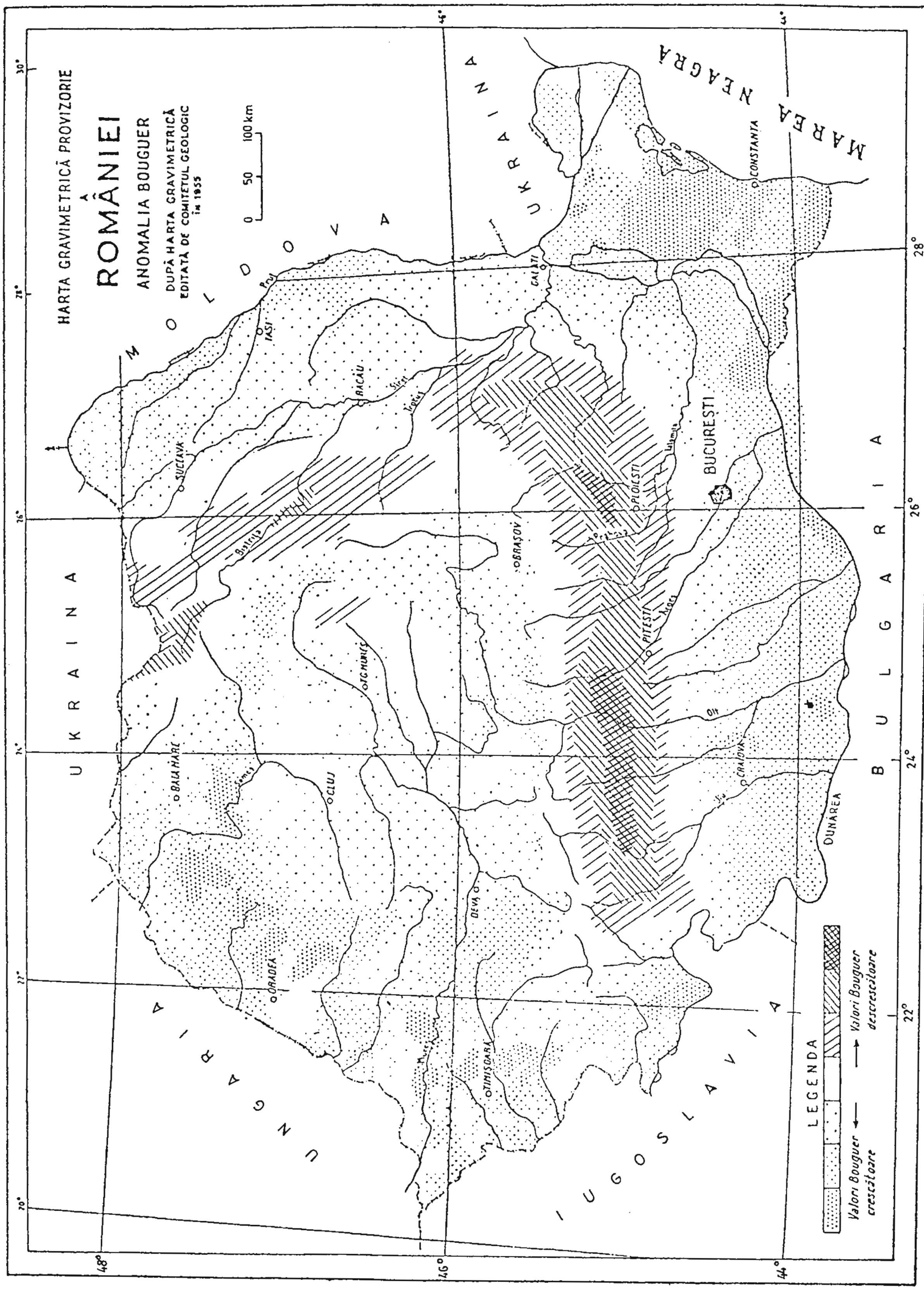

HARTA GRAVIMETRICĂ PROVIZORIE
A
ROMÂNIEI
ANOMALIA BOUGUER
DUPĂ HARTA GRAVIMETRICĂ
EDITATĂ DE COMITETUL GEOLOGIC
în 1955
0 50 100 km
U K R A I N A
M O L D O V A
U K R A I N A
MAREA NEAGRA
B U L G A R I A
I U G O S L A V I A
U N G A R I A
SUCEAVA
IAŞI
BACĂU
GALAŢI
CONSTANŢA
BRAŞOV
PLOIEŞTI
BUCUREŞTI
PITEŞTI
CRAIOVA
TG. MUREŞ
CLUJ
BAIA MARE
ORADEA
DEVA
TIMIŞOARA
Siret
Bistriţa
Prut
Olt
Jiu
Mureş
Someş
Argeş
Prahova
Ialomiţa
DUNAREA
LEGENDA
Valori Bouguer crescătoare
Valori Bouguer descrescătoare

Fig. 1 - 10

Fig.1-11

The Mohorovičić discontinuity in Romania inferred from gravity data (after Socolescu et al.,1964). This map is now outdated since the publishing of the DSS data for the crustal structure of Romania. It gives,however, comparable values to the Moho in the Dobrogea and Pannonian regions, on either side of the Vrançea mountains (solid circle).

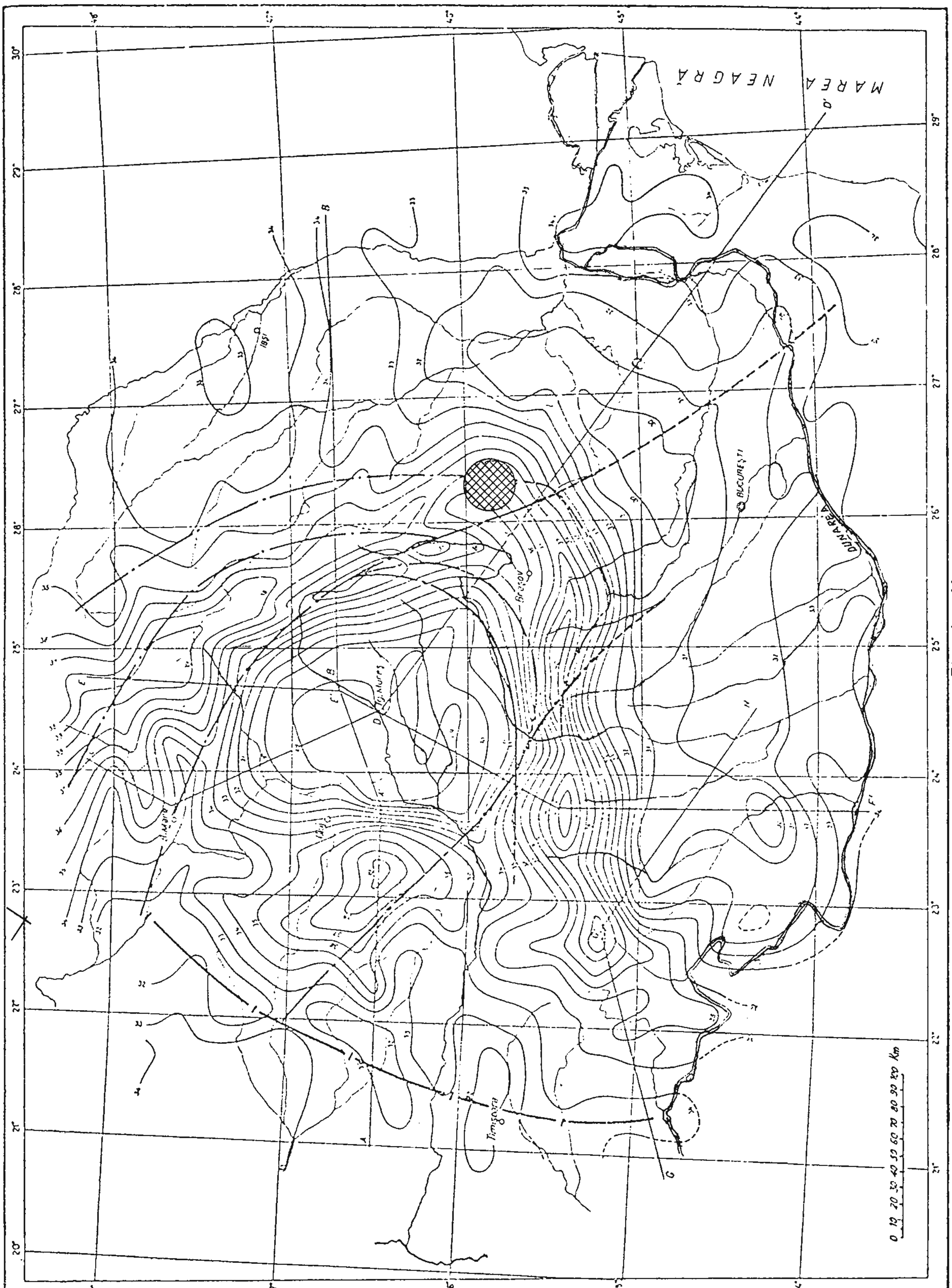

MAREA NEAGRĂ
BUCUREŞTI
DUNĂREA
Braşov
Tg. Mureş
Timişoara
0 10 20 30 40 50 60 70 80 90 100 Km

Fig. 1 – 11

continentalisation process in the Panonian than in the Black Sea basin. These absolute values for the earth's crust in East Europe all round the Carpathian arc substantiate the model we proposed for the tectonic evolution of the area.

The seismological data also produced useful information as to the physical quality of the basement from a map of isoseismals (Atanasiu, 1961), travel-time anomalies (Roman, 1973 and chapter 2.2) or the map of isovelocities computed from explosion seismology (logging) (Ciocârdel, Socolescu and Popescu, 1972). (figs. 1-8 and 1-9).

1.3.1 Gravity

As already pointed out in the introduction to the geophysical properties of the Carpathians, the main difficulty in considering the quality of the gravity information available from the Romanian literature is the lack of quantitative maps - only qualitative maps (with shadings but no absolute values) are available. Looking at such a map presented by Ciocârdel and Esca (1966) (fig. 1-10), the general trend of the Bouguer negative anomalies follows the trend of the Carpathian arc. More precisely one could say that the negative Bouguer anomalies coincide with the region of the sub-Carpathian foredeeps; this is hardly surprising, as the packet of accumulated sediments is very thick indeed in all Alpine foredeeps. Therefore, the Carpathians are no exception to the rule and no particular correlation could be established between the subcrustal nest of foci at the elbow of the mountain arc (the Vrancea mountains) and the negative Bouguer anomaly.

Of greater value is the correlation between the positive Bouguer values on either side of the Vrancea mountains, at the SE in the Dobrogea region, very close to the Black Sea basin, and to the NW in the Panonian basin of Western Transylvania; they suggest a similar structure of the earth's crust corresponding to a basaltic layer overlain by a packet of sediments granitized at the bottom. Thus the crust on either side of the Carpathian arc underwent the same history, starting as an oceanic type of crust (towards the Black Sea, this was part of the Tethys oceanic floor, while in the Panonian basin it was an internal sea linked to the western Mediterranean - fig. 1-7). This has undergone a continentalisation process of the type described by Menard (1967), more pronounced in the Panonian basin, where the crust has become a continental type, and still incomplete in the Black Sea basin, where there is an intermediate type of crust (Roman, 1970, 1971). This point of view was later substantiated by DSS in these regions (see chapter 1.3.3).

Of still greater value to us would have been the original data used by the authors (Ciocârdel and Esca, 1966) in computing their Bouguer reduced map. But a free air gravity map is unavailable in Eastern Europe. The same handicap applies when one considers the map of the Moho discontinuity computed (fig.1-11) from free air gravity data by Socolescu et al. (1964), as we are presented only with the end-product, not with the original free air gravity map on which these computations were carried out. The map of the Moho discontinuity with which we do not agree has become obsolete by recent DSS observations carried out by Enescu et al. (1972), which differ by as much as 10-15 km for SE Dobrogea. Still these results based on gravity measurements outlining the features of the Moho (Socolescu et al., 1964) are presented in figure 1-11 merely to show the general trend along the major tectonic units and to compare relative values for Dobrogea and the Panonian basin, even though they are erroneous.

There are only two isolated values confirming the steep isostatic gradient across the Carpathian arc: -60 mgals at Focsani (in the Carpathian foredeeps) and +70 mgals at Fagaras (in the Transylvanian basin); this gives an average gradient of 1 mgal/km, decreasing from west to east across the Vrancea mountains (Petrescu and Radu, 1965).

1.3.2 Heat Flow

The general picture which characterises the heat flow anomaly on either side of the Vrancea's intermediate earthquake zone is very simple indeed: at the west, in the Panonian and Transylvanian basins, there is a high heat flow, followed by a low heat flow in the region of the Carpathian flysch; at the east, in the zone external to the Carpathian arc (the Russian Platform and the Black Sea basin) there is a normal heat flow (Roman, 1970).(fig.1-23).

The Intra-Carpathian Basin (Panonia and Transylvania): heat flow measurements from Hungary are presented by Boldizsàr (1964) who gives an average value of 2.4 h.f.u. This value makes the Panonian heat flow the most important in Europe. The heat flow measured in Slovakia (Boldizsàr, 1965) is part of the same high anomaly: 2.66 h.f.u. at Banska Striavnica.

Transylvania, like Slovakia, is part of the same heat flow zone as Hungary. However, no geothermal data from the boreholes in Transylvania have been released. The only information one has in connection with the heat flow comes from geological observations. It is known that the whole intra-Carpathian basin of Panonia-Slovakia-Transylvania is rich in thermal springs. Oncescu (1959) quotes temperatures of 20.8°C at Tusnad, 23.6 - 26.7°C at Toplita, 20 - 22.5°C at Lobogo, and 22.5°C at Lunca, which are all spas on the Transylvanian side of the Eastern Carpathians; west of the Transylvanian Alps, near the city of Oradea, there are lakes with temperatures from 41°C to 48°C (in these lakes a unique lily from Tertiary times (70 my ago) has been preserved, the Nymphaea Lotus Thermalis).

The Carpathian Flysch: this zone is characterised by a low heat flow. There are nevertheless few measurements quoted in the literature, ranging from 0.75 to 1.35 h.f.u. (Boldizsàr, 1968), the lower values being on the flysch side of the Carpathians and the higher values of the range towards the Carpathian foredeeps.

The Russian Platform is quoted by Sollogub and Mihailova (1969) as having an average of 1.05 ± 0.1 h.f.u.

The Black Sea Basin (with the exception of some very localised high heat flow values in the Crimea and the Caucasus, connected with active fractures) has a normal heat flow of 1.2 h.f.u. (Lee and Uyeda, 1965).

1.3.3 Deep seismic sounding

Since the late 1960's the Carpathian-Balkan commission for Geology and Geophysics designed a series of profiles along which deep seismic sounding should be carried out in SE Europe, in order to investigate the structure of the crust. In 1969 none of these profiles was supposed to cross the Carpathian elbow (Prosen , 1969), which should be by far the most interesting from the seismotectonic point of view and for our understanding of the subcrustal phenomena. In 1970, at the 9th assembly of the European seismological commission in Luxemburg, I proposed (Roman, 1971) that one of the DSS profiles should cross the zone of lithospheric underthrust. At present some of these observations have just been published and commented on by Enescu et al. (1972) and Constantinescu et al. (1972) (fig. 1-12).

These results are of the utmost importance because they give absolute values for the crustal structure in the Vrancea foredeep. They show the tectonic accidents and their geometry, which might be indicative of the possible plate boundaries linking the Carpathian lithospheric underthrust to recognised plate boundaries in the Crimea (profile XI, fig. 1-11) and also because they substantiate our interpretation of the gravity anomalies for the Dobrogea and the Panonian basin (profiles II and III, fig. 1-12).

The review of the DSS findings is presented below:

1. The sedimentary layer of the Carpathian foredeep behaves as a continuous medium from the seismic point of view (e.g. velocity increases with depth). Two discontinuities

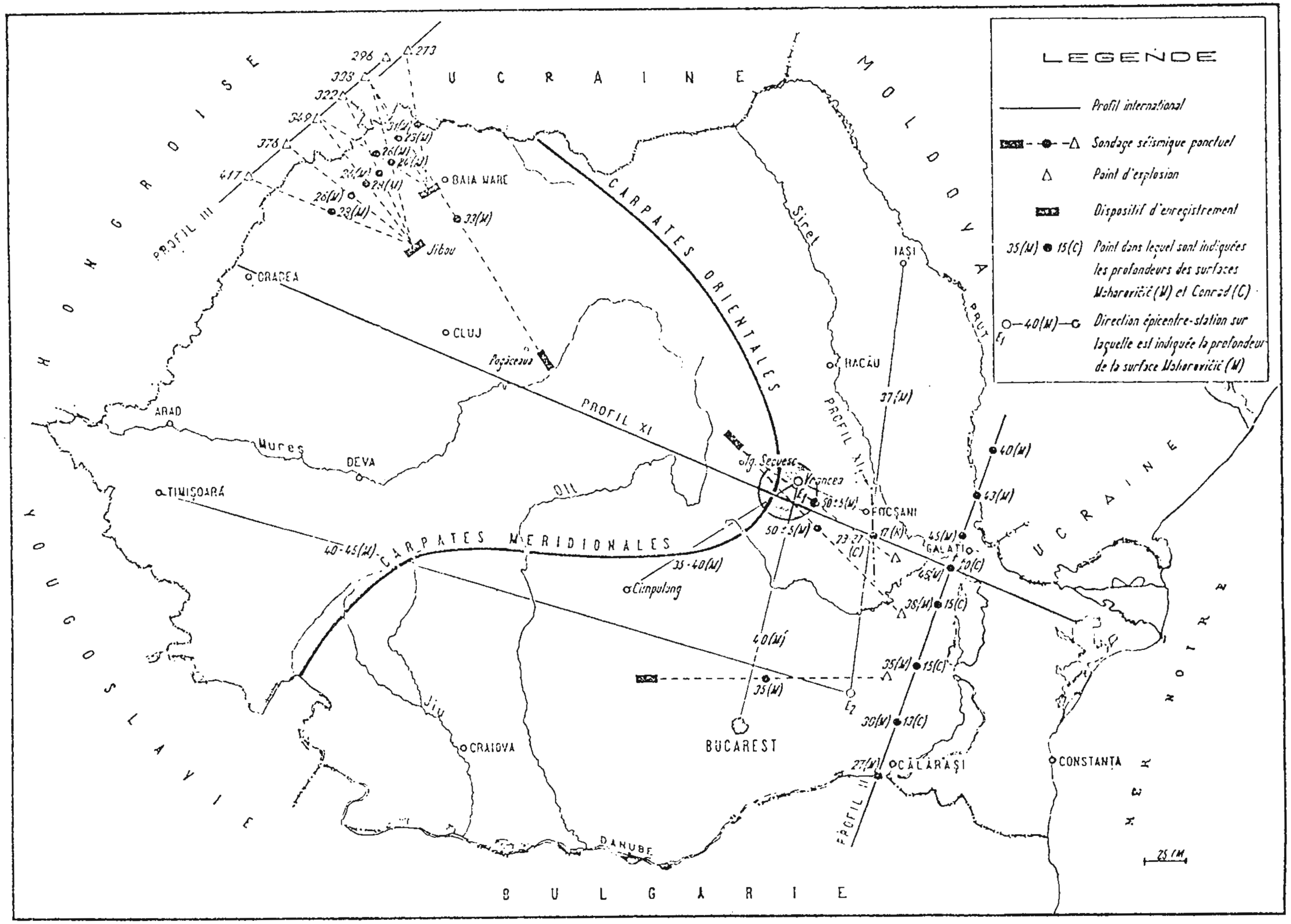


Fig.1-12

Deep Seismic Sounding (DSS) profiles (after Constantinescu et al.,1972). Profile XI crosses the Carpathian arc in the Vrancea region which allows for the exact estimate of of the earth's crust in the zone of lithospheric underthrust. Profiles II and III confirm the expectation from the gravity maps, namely that the crustal structure in the Pannonian basin and in Dobrogea are comparable.

were found within the sedimentary at 4-5 km, V_L = 4.2 km/sec, at the level of the Pliocene (probably the lower Pliocene, e.g. Pontian or Meotian, 10 my), and at 10-11 km depth, V_L = 5.6 km/sec (Jurassic or Triassic, e.g. 180 or 230 my ago). The Carpathian foredeep at Focsani presents a uniquely thick packet of sediments of 18 km.

2. The Conrad discontinuity at the Carpathian elbow is deeper (26-28 km) and decreases north and south of the elbow to 20-23 km; the same pattern applies to the Moho discontinuity, which presents a cuvette external to the elbow of the mountain arc. The earth's crust increases its thickness from east to west along the profile XI: 42-44 km at the easternmost limit of profile XI, then 47 km at Focsani and finally 50-55 km under the Carpathians.

3. There is another discontinuity deeper down than the Moho, at 80-90 km, which is interpreted by the authors (Enescu et al., 1972) as the upper limit of the low velocity layer. The lower limit of the low velocity layer appears from P-wave data at a depth of 250 km and from S-wave data at 400 km.

Comments on the seismotectonic implications of the DSS data

Firstly, it would be valuable to compare the Romanian DSS observations with DSS values obtained for similar tectonic units within the Alpine system of Europe.(table 1-1).

Reference	Crystalline layer km	V_l km/sec	Conrad km	V_k km/sec	Moho km	V_m km/sec	Tectonic unit
Sollogub et al.,1969					45-50		Crimean Mts.
Sollogub et al.,1969					22-30		Black Sea
Enescu et al., 1972	17-18	6.5	26-27		42-54		Carpathian foredeep
Dohr 1969			14-20		28-42		pre-Alps and Alps
Dragashevitch 1971	1.9 - 3.1				25.5 - 31.2		Panonian basin
Mituch 1969					27.5	8.1	Panonian basin
Prosen 1969	5		25				Bohemian Mts.

Table 1-1

The alpine crust from DSS data

A very brief consideration of the above figures allows us to see that the DSS confirms the interpretation originally made from gravity data (Roman, 1970, 1971), showing the (fig.1-13) similarity between the structure of the crust in the Black Sea region and that in the Panonian basin; also it is clear that the Moho values obtained for the Carpathians are similar to those found for the western Alps. The above more general consideration supports the continentalisation process on either side of the Carpathian arc. It compares the crustal structure of the Carpathians with the western Alpine system and suggests that there are no differences in the Moho values between the Eastern Carpathians and the Western Alps.

So far as the sedimentary layer external to the Carpathian elbow (the Vrancea Mountains) is concerned, the implications of the DSS observations are extremely valuable for two reasons: firstly, it shows a cuvette containing the thickest packet of sediments ever found in an Alpine foredeep and, secondly, it shows that the sediments accumulate since the Pliocene (10 my ago) are only 4-5 km deep. With respect to the first point, the presence of the cuvette can be associated with the existence of a process of subsidence localised at the elbow of the mountain arc, external to the zone of intermediate depth foci; as for the second point, it clarifies the fact that not the entire packet of sediments of 18 km was accumulated through gravitational force since the beginning of the Alpine orogeny, some 18 my ago, but only a fraction of it, from 4-5 km. The remainder of 13-14 km go back to Jurassic or Triassic times, that is, some 180 or 230 my ago.

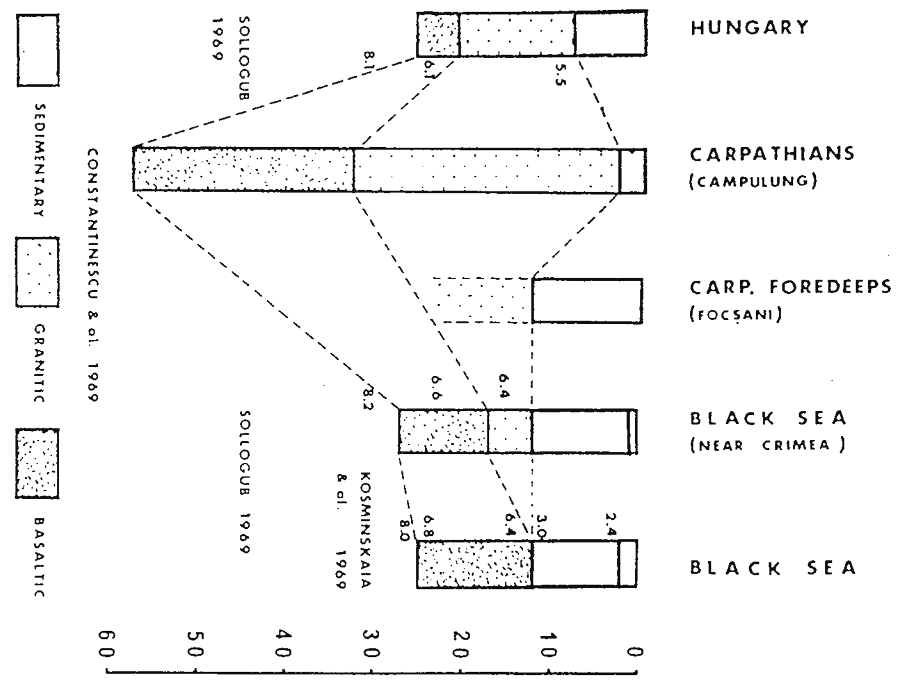


Fig.1-13

Crustal structure profile in SE Europe (after Roman,1971). Note the similarity between the crustal structure in Hungary and the one near Crimea, in the Black Sea: they both started as typically oceanic crust and subsequently underwent a process of continentalisation, now complete in the Pannonian basin, but still going on in the region of the Black Sea.

It is therefore very simple to deduce the average rate of sedimentation for the past 10 my, which is 5×10^5 cm/ 10^7 yr = 0.5 mm/yr. Considering that for the same period of time the average sinking rate of the lithosphere was 1.6 cm/yr, which is 30-40 times as much, it is not clear whether the lithospheric underthrust should be altogether responsible for the thickness of a layer which at the 0.5 mm/yr rate of sedimentation could have accumulated in normal circumstances. If one computes the average sedimentation rate for the past 180 my, that is, 18×10^5 cm/18×10^7 yr = 0.01 cm/yr = 0.1 mm/yr, then it seems even more plausible that this rate, since the Jurassic, occurred in the normal conditions without any specific link with the gravitational accumulation of sediments.

Lastly, it is worth noting the discontinuity below the Moho at 80-90 km, which coincides with the depth at which the Bolt relocation of hypocentres (Roman, 1970) shows an increase in the seismic activity.(fig.1-16).

1.3.4 Seismicity in Romania - a case history

The historical earthquakes in Romania are mentioned in a number of chronicles or in notes made by monks ('letopiset') and they are related to contemporary historical and political events.(the letopiset of the Bistrita monastery: 1359-1506; the Serbo-Moldavian chronicle of the Neamt monastery: 1325-1512; the Moldavian-Polish chronicle of Nicholas Brzeski: 1359-1566; the chronicle of Moldavia and Wallachia by Miron Costin, 1684). Details on Transylvania, where some of the Vrancea earthquakes were felt, are found in the Saxon and Hungarian chronicles. Earlier, when the Black Sea coast of Romània was part of the Byzantine empire or, prior to that, part of the Roman empire and Greek colonies (belonging to the city of Milletus in Asia Minor), more evidence can be found about ancient earthquakes.

A review of these sources is presented by Draghiceanu (1896), Stefanescu (1901), Popescu (1938) and, more recently, by Atanasiu (1961). The most important of these historical earthquakes are the ones with epicentres at the Carpathian arc, known as "Moldavian earthquakes". A series of the larger shocks, some of which are destructive, is presented by Atanasiu (1961): 1170, 1196, 07.02.1258, 24.11.1516, 08.11.1620, 11.06.1701, 11.06.1738, 06.04.1790, 26.10.1802, 10.02.1821, 26.11.1829, 23.01.1838, 13.11.1868. Since the turn of the century the installation of seismic stations on the territory of Romania allowed the recording of smaller earthquakes.

It is not our intention to mention all studies of seismicity made in Romania, the more recent of these are included in the reference list at the end. We shall only extract from these papers a few ideas, to show what was already known before the present study was started and to show what is still to be done.

Epicentre distribution. There are many papers giving lists of epicentres:

Popescu (1957): 1,800 epicentres

Radu (1965): 559 epicentres, between 1901-1963

Sacuiu and Zorilescu (1968): 377 events, 1937-1962, $2.3 < m < 7.5$

Niculescu (1968): 567 events, 1800-1963.

The quality of the epicentral distribution for the above events is poor. Perhaps the most valuable study in this respect is that of Radu (1968) which finds a N 30°E orientation of the epicentral region at the Carpathian arc, and that of Iosif (1968) who gives an orientation of N 30°E computed from P waves and of N 60°E computed from S waves. The study by Iosif (1968) is based on 77 events of magnitude smaller than 5.0 between 1952 and 1966, and he finds a difference in the epicentral location between the P waves and S waves methods varying from 8 to 22 km. However, the results of Iosif computed from S wave data are wrong, since in many cases the author assumes automatically the co-ordinates, $\varphi = 45.7N$; $\lambda = 26.6E$, when the event is not located.

Hypocentre distribution. The approximate depth of the intermediate foci under the Carpathian arc was known for some time (Jeffreys, 1935; Gutenberg and Richter, 1938) and it was often quoted to be at some 150 km depth. In the Romanian literature there is no consistent difference in the definition of "shallow" and intermediate depth events. Radu (1968) includes in the category of shallow earthquakes all foci up to 100 km and the same author, in a different article of the same year, quotes 80 km as the maximum depth of shallow events. He mentions the occurrence of sub-crustal foci up to a depth of 200 km. Iosif (1968), in his study of the 77 subcrustal events between 1952 and 1966, finds the nest of subcrustal foci stretching from 80 to 160 km depth. This evaluation is closer to reality, but a more careful consideration of the results reveals that these events have strangely the same increment of 5 km in the estimates of focal depth; the distribution of epicentres is available, but not of the hypocentres of the same events. Also no explanation is given for the confinement of foci within such a small space under the mountain arc. Even arbitrarily assuming that some of the epicentral values were situated at 45.7N; 26.6E, this spatial distribution of foci would be erroneous. Radu (1968) underlines in his conclusions that no apparent correlation exists between the shallow and the intermediate depth events at the Carpathian arc.

Low velocity layer. Iosif (1965a) finds a low velocity layer between 100 and 200 km depth, by studying the P and S waves of intermediate depth events; for the Vrancea Mountains Iosif (1965b) states that the low velocity layer, as suggested by the study of shear waves (S waves), stretches between 100 and 250 km.

Magnitudes. There are two studies carried out by Radu (1964 and 1968) on the magnitudes of Carpathian earthquakes. The latter study is based on observations of some 160 events, at intermediate depths, which occurred between 1942 and 1960, having a magnitude span of $3.1 \leqslant m_{SH} \leqslant 6.5$, and of 18 shallow events ($h < 80$ km) between 1943 and 1962. The author uses the formula where the energy is a function of the period of oscillation, $\log E = 16.51 + 3.21 \lg t$, but $\log E = 11.8 + 1.5M$; so he finds for the Carpathians' subcrustal events that:

$$M_t = 2.14 \lg t + 3.14$$

which is similar to the formula found for the Hindu Kush subcrustal events of:

$$M_t = 2.12 \lg t + 2.87$$

For the shallow events, Iosif (1968) uses the formula $\log E = 16.15 + 2.781 \lg t$, so that he finds:

$$M_t = 2.12 \lg t + 2.66$$

for the Carpathians, which compares with the Hindu Kush shallow events as follows:

$$M_t = 2.0 \lg t + 2.46.$$

A 20% error in the period of oscillation results in a ± 0.2 error in the estimate of the magnitude M_S. Iosif (1968) also makes an interesting remark, showing that for the same magnitude the period of intermediate foci earthquakes is shorter than that of the shallow earthquakes.

Frequency. In terms of "seismic risk", Sacuiu and Zorilescu (1968) claim that every 120 years there should be a destructive earthquake comparable to the one of 10.11.1940, which was of magnitude 7.5 (MM); their study is based on the statistical analysis of some 377 events which occurred between 1937 and 1962.

So far as the magnitude-frequency study is concerned, it is almost always difficult to compare the "b" values computed by various authors, since they use different magnitude scales and different areas, and consequently the physical significance (if there is one at all) is not the same. However, one should mention a value of b = 0.80 (Karnik, 1969) and another value of b = 0.76 (Constantinescu and Enescu, 1964) for the Carpathians. Radu (1965) finds for the Vrancea a value of b = 1.5.

Energy. Constantinescu and Enescu (1964) computed the amount of energy released through seismic activity at the

Carpathian arc, between 1937 and 1962, as $E = 8.76 \times 10^{22}$ ergs, out of which 90% was released by one major shock on 10.11.1940. The average of 0.33×10^{22} erg/yr of Constantinescu and Enescu (1964) for 1937-1962 is about three times as much as the average found by Radu (1965) for the period 1601-1963: 0.86×10^{21} erg/yr. This is hardly surprising considering that since 1601 until the 20th century a lot of the smaller tremors must have been left out and that the energy would have been more difficult to estimate than for the more recent events. For the period 1901-1963 Radu (1965) finds an energy of $E = 11.24 \times 10^{22}$ ergs which gives a yearly average of 0.18×10^{22} ergs/yr; this, though more accurate than the previous average, is about twice as small as Constantinescu's figure of 0.33×10^{22} ergs/yr.

Travel-time residuals. Petrescu et al. (1965), in a study of intermediate depth foci from the Carpathians, find early arrivals for stations with a $\Delta < 25^{\circ}$ and late arrivals for stations with a $25^{\circ} < \Delta < 35^{\circ}$; for shallow events they find almost the reverse, that is, late arrivals for stations with a $\Delta < 13.5^{\circ}$ and early arrivals for seismic stations with a $\Delta > 13.5^{\circ}$; unfortunately, the conception of shallow for this study includes hypocentres up to 100 km depth and the events are not relocated. The method made use of the pP waves (which are the waves reflected at the crust in the neighbourhood of the epicentre). Iosif and Iosif (1968) point out in their study of the spectra of seismic waves from the intermediate depth foci in the Vrancea mountains that the arrival of the waves is influenced by the geological structure underneath the receiving station; this coincides with our study of the travel-time residuals (Roman, 1973c). The correlation between the geological structure and the transmission of the longitudinal waves is emphasised by Ciocârdel et al. (1972).

Focal mechanisms. Constantinescu and Enescu (1963) and Constantinescu et al. (1966) computed a number of focal mechanisms of Carpathian earthquakes between 1934 and 1960(fig.1-25) and found most of the events of a thrust type with a strike-slip component. Only three events (29.03.1934; 12.03.1945 and 19.12.1945) are a combination of normal faulting with strike-slip, but they are very likely crustal events. Radu and Purcaru (1964) also note a prevailing thrust type of mechanisms as opposed to the normal faulting. They also point out that the compressional axes of the Carpathian earthquakes are horizontal. Ritsema (1967) also computed some focal mechanisms of the Carpathian earthquakes, but he presents average solutions for groups of events and, as these are not relocated, it may happen that the same group should include shallow and intermediate depth foci at the same time - or these tend to have a different type of mechanism (thrust for the intermediate depth foci and normal faulting for the shallow foci).(fig.1-25).

Comments on the study of seismicity in Romania by other authors

What is lacking so far in the specialist literature on the seismicity under the Carpathian arc is a unified view of the seismic phenomena, an overall accurate evaluation of the parameters and their correlation with other geophysical and geological features. In the 1960's attempts at "geophysical integration" of seismic data were made but the conclusions were marred by poor results. Individual papers may have some valuable results which we shall use as a means of comparison in chapter 2, and also in our interpretation in chapter 3, but as a whole the few good results are obscured by a mass of very inaccurate observations, poor qualitative methods in the data processing, and general lack of perspective in the interpretation.

As a consequence of the above situation, it appeared necessary to re-evaluate the seismic parameters (epicentre and hypocentre relocation, re-evaluation of the origin times, travel-time residuals) to distinguish between the good and poor quality work done so far and to reinterpret it all. These aspects will be dealt with in the following chapters.

B. data processing

CHAPTER 2

Seismological Study of the Vrancea Earthquakes

The Vrancea earthquakes have already been the subject of several of our papers (Roman, 1970, 1971, 1973a,c) and seminars (1970-1973).

70 events between 1928 and 1965 were relocated at Cambridge by making use of Bolt's (1960) program. New origin times were found and the residuals were plotted on a focal sphere for each individual event (see appendix for figures).

A first interpretation of the geometrical significance of the focal distribution was presented (Roman, 1970) in terms of plate tectonics theory. A two-dimensional plate model, and a first crude estimate of a possible thermic model for the Carpathian arc, were presented to the 9th European Seismological Commission, at Luxemburg, in September 1970 (Roman, 1971).

As the study of the travel-time residuals computed through Bolt's program did not appear to show the expected pattern of anomalies (Davies and McKenzie, 1969), a parallel method of relocation was tried, by using the joint epicentre determination (JED) method (Douglas, 1966). The processing was carried out at Blacknest. This time only 58 out of the previous 70 relocated events were used for the same period 1928-1965. The epicentre distribution as computed through JED presents a more concentrated area of seismicity than the distribution of epicentres relocated through the Bolt program: some of the events which were originally situated in Transylvania behind the Carpathian arc (a region considered as aseismical) were now pulled in front of the mountain arc, together with the bulk of the epicentres; these were probably shocks of a lesser magnitude which occurred in the late 1920's and the early 1930's, some of which were recorded at seismic stations which have since ceased to function. Events of the same magnitude occurring in the 50's and 60's would automatically be better located due to an improved number of stations which functioned long enough to allow good estimates of the average travel-time residuals to be made. A comparative presentation of the epicentre location through Bolt and JED programs is published (Roman, 1973c) and is presented in chapter 2.1.3, and a study of the residuals in chapter 2.2.

The focal mechanisms of the Carpathian events were not studied for two reasons: (a) since the installation of the standard seismic network, the WWSSN, in 1962, large enough shocks did not occur to determine a reliable mechanism; (b) some of the mechanisms since 1934 were reasonably well defined by Constantinescu et al. (1966) using observations of seismograms from non-standard stations, and these appear to fit in well with the general interpretation of our results (Roman, 1970). Furthermore, the zone of subcrustal events, like the one under the Carpathian arc or the Hindu Kush, would understandably produce thrust mechanisms whose nodal planes were in the same azimuth as the plane of the sinking lithosphere, so that no surprise could be expected there. Far more interesting would be the study of shallow events to determine the movement of the crust off the Carpathian arc, along the fault lines linking the elbow of the mountains (the Vrancea

Mountains) to the Crimean thrust fault, north of the Black Sea. Here the difficulty lies in the relatively reduced seismic activity and in the fact that shallow events are of lesser magnitude than the intermediate depth shocks at the arc.

A general interpretation of these results is presented in chapter 3.

2.1 Relocation methods

The source of errors in epicentre location could be due to:

(a) an error in the estimate of the onset time of the first arrival;

(b) lack of station correction required by the varying geological structures beneath the recording station;

(c) a possible structural variation about the source (source bias; Douglas and Lilwall, 1968);

(d) errors in the computation of the travel-time curve used for finding the best least squares fit of the first arrivals.

All these sources of error are likely to introduce large travel-time residuals and consequently wrong estimates, especially for the smaller magnitude earthquakes, since the corrections are greater for the nearer seismic stations because shallow ray paths are confined to the inhomogeneous crust and upper mantle. In the normal course of events for large earthquakes these effects at close and distant stations are averaged out.

The two relocation methods used are well presented by their respective authors (Bolt, 1960, and Douglas, 1966); so we shall content ourselves with briefly presenting the principles only.

Bolt's method of relocation fits the observations of P and PKP travel-times to the times in the Jeffreys-Bullen tables by the least squares method. The number of the equation of condition can be reduced by combining groups of stations with similar distance and azimuth. The following are the main steps:

1. The condition equation is repeated for "n" stations, taking the travel-time residuals as a function of the following parameters:

   (a) the true origin time τ

   (b) the co-ordinates of the true focus (x,y,z)

   (c) distance (Δ) and azimuth (α) of the station from the trial epicentre

   (d) the theoretical P or PKP travel-time to distance Δ (t).

The equation is:

$$\xi = \tau - (x \sin\alpha + y \cos\alpha) \frac{\partial t(\Delta)_z}{\partial \Delta} + z \frac{\partial t(z)}{\partial z}$$

2. A weighting technique is used to remove the large residuals, due to observational or copying errors, before these observations are incorporated in a least squares solution.

3. After the weighting operation two matrices are formed:
A: n(nr of observations) X 4 (nr of coefficients τ,x,y,z)
B: n X 1, formed by residuals ξ_i.

4. The epicentre distance and azimuths are computed for the observing stations from the epicentres, after computing the geocentric direction cosines from the co-ordinates.

5. Elipticity adjustments are introduced.

6. The derivatives $\partial t/\partial\Delta$ and $\partial t/\partial z$ are computed.

7. The columns of the highest element are searched before pivoting.

8. Matrix elements are reduced by 100 and the resulting correction is scaled accordingly to focal depths.

9. For the normal earthquakes only one column of the matrix with travel-time residuals is entered.

10. For intermediate earthquakes both the P and pP travel-time residuals are taken into account.

11. The solution provides ζ,x,y,z which are used to revise the trial origin-time, epicentre and focal depth.

12. After each iteration a root-mean-square and a standard error are computed relative to the new weighting function.

13. Iterations are stopped when $|x|$, $|y| < 0.1^\circ$ and $|\zeta| < 0.1$ sec.

Remarks on the Bolt's method of revision of epicentres, focal depths and origin-times.

Part of the procedure of the relocation program, which reduces the equations of condition, combines groups of stations according to their distance and azimuth from the trial epicentre. This practice has certain disadvantages, as can be seen in chapter 2.1.3, where a comparison is made between the epicentre creation computed through Bolt's program and those obtained through the joint epicentre determination (JED)(f.1-17 program. In addition, it is known (see chapter 2.2), by observing the travel-time residuals, that some seismic stations have systematic late arrivals and some have early arrivals. Bolt's program produces a list of residuals for each individual event but not average P-travel-time residuals for all Carpathian events at each individual station, as does JED. A quick glance at the pattern of the anomalous late arrivals (fig. 1-20) is enough to realise that the cause of the anomaly lies not under the source but under the station itself, and is due to the structure of the lithosphere. The seismic stations grouped according to their distance and azimuthal angle from the epicentre will not all have the same type of crust beneath them. This is obvious for the case of the Carpathians where most of the Russian stations would be situated on an old continental platform, while the seismic stations of the Panonian basin (at comparable distance from the Carpathian epicentres) would be situated on a young continental crust, where the high heat flow and the crustal structure would produce late arrivals. Through such a grouping of seismic stations one can introduce a certain error in the location of those events which are of a lesser magnitude, received only by a limited number of seismic stations close to the epicentre. This is how some of the shallow events at the Carpathian arc (see chapter 2.1.1) appear wrongly located in Transylvania, a region known to be seismically inactive - a hinterland compared to the Carpathian foreland.(fig.1-15).

If an earthquake is well observed, the standard error in

Flow Diagram

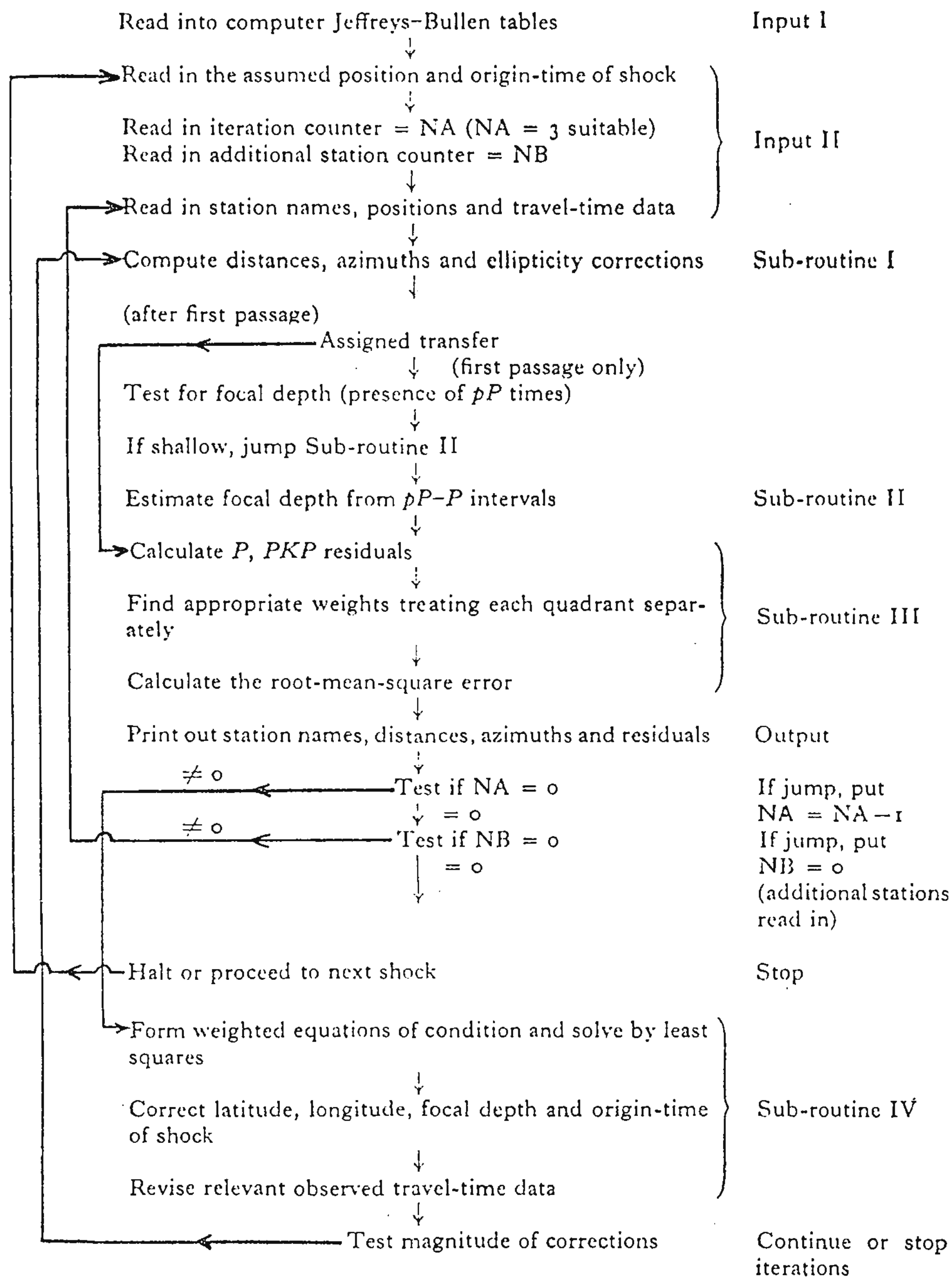


Fig.1-14

Flow diagram of Bolt's relocation program (after Bolt,1960). The program as we used it was slightly modified by Davies & McKenzie (1969) to allow for the plotting of the residual spheres of P travel-times, which we present in chapter 2.2 and in the addendum I.

the epicentral latitude and longitude is about 0.05°, that is, within 5 km from the true epicentre (Jeffreys, 1959). For the Bikini atomic explosion of 28 February 1954, Bolt (1960) finds a standard error of 1.25 seconds.

In order to make a qualitative evaluation of each of the epicentre locations at the Carpathian arc all the focal spheres containing the distribution of residuals are presented in the appendix at the end of Part I of this work. There it appears obvious that, where there are few residuals (e.g. few seismic observations) and the stations are not evenly distributed, the location is less accurate.

For a clearer presentation of the Bolt program, a flow-diagram is shown in figure 1-14.

Remarks on the Joint Epicentre Determination (JED) method: revision of epicentres and origin times.

This method of relocation was developed by Douglas (1967). The principle of the JED method is to compute the total travel-time correction, the position, and the origin-time of a group of earthquakes simultaneously, using the following equation of condition:

$$\delta S_j + \delta H_i + \delta h_i \frac{\partial T}{\partial h_i} + x_i \cos\alpha_{ij} \frac{\partial T}{\partial \Delta_{ij}} - y_i \sin\alpha_{ij} \frac{\partial T}{\partial \Delta_{ij}} = \delta T_{ij}$$

where

$\partial T_{ij} = A_{ij} - H_i - T_{ij} - S_j$

S_j = the j^{th} station correction

H_i = the approximate origin-time of the i^{th} event

h_i = the approximate depth of the i^{th} event

Δ_{ij} = the distance from the approximate epicentre of the i^{th} event to station j

$_{ij}$ = the azimuth from the approximate epicentre of the i^{th} event to station j

A_{ij} = the time of the first arrival at station j of the i^{th} event

T_{ij} = the travel time of the P wave from the approximate epicentre of the i^{th} event to station j

$\frac{\partial T}{\partial \Delta_{ij}}$ = the partial derivative of the travel time with respect to distance at the point Δ_{ij}, h_i

$\frac{\partial T}{\partial h_i}$ = the partial derivative of the travel time with respect to depth at Δ_{ij}, h_i

$\frac{\partial T}{\partial \Delta_{ij}}$ and $\frac{\partial T}{\partial h_i}$ are obtained from travel time tables.

The depths h_i for the Carpathian earthquakes were restrained at the values computed through Bolt's program, which were considered to be satisfactory. Since the equation of condition cannot be solved uniquely, a supplementary condition has to be applied: for the Carpathians we preferred to any of the other possible conditions (the sum of the station corrections S_j be made equal to zero; and one of the S_j terms be specified) to choose the condition of restraining in time and position the largest magnitude event of 10 November 1940, called "the master event", as it has a large number of seismic station recordings (i.e. 148 stations) and a good azimuthal distribution of seismic stations (fig. 1-18). The location of the master event of 10 November 1940 was computed through Bolt's program, and from table 1-3 one can see that this earthquake's relocation is quite reliable (SELAT = 6.1 km; SELON = 2.7 km; SEDEPTH = 6.0 km; SETIME = 0.6 seconds).

The reason why we dropped the condition $\sum S_j = 0$ is that this is normally applied when the events are spread over a wide area and so the varying geological structures beneath the recording stations (station corrections) can be evened out. Furthermore, we could not use the alternative condition of specifying one of the S_j terms, as we could not derive it from a nuclear explosion anywhere near our epicentral area. For these reasons we introduced the condition of restraining the parameters of a master event.

A comparative table of epicentral relocations through Bolt and JED programs and a comparative epicentral map are presented in chapter 2.1.3. At this stage one can state with certainty that the JED relocation method seems to be more advantageous than Bolt's method for the simple reason that the nest of seismic activity is concentrated within a very small area, thus allowing good station corrections to be made in the region close to the epicentres at stations which are most important for the estimate of the epicentral location of small magnitude earthquakes. Bearing in mind that seismic activity at the

Carpathian arc is rather weak, one can see immediately why it is important to have good relocations of smaller magnitudes (see chapter 1.3.4).

2.1.1 Shallow events at the Carpathian arc

The spatial distribution and origin times of the shallow events at the Carpathian arc, after they have been relocated through Bolt's program, can be seen in figure 1-15 and table 1-2.

The seismic observations of the trial locations of the events, and times of arrivals of the P waves, come from the bulletins of the BCIS and ISC issued between 1928 and 1965. Comments on the quality of the relocations are summarised below:

(1) A shallow event is considered to have a focus within 50 km of the surface; this is a fair assumption for the average crust at the Carpathian arc.

(2) For a given period of time and range of magnitudes, there is a considerable smaller number of shallow events than of intermediate depth events at the Carpathian arc. There is also a tendency for the shallow seismicity to have a lower magnitude span than the intermediate depth seismicity.

(3) The majority of shallow events are external to the Carpathian arc (those very few events which appear behind the arc, in the region of Transylvania, are very likely mislocations).

(4) There is no particular correlation between the local tectonics and the distribution of shallow epicentres, as there is no apparent trend in the spatial distribution of these events (fig. 1-1).

(5) The focal depth is rather poorly located because of the limited number of seismic observations (see column 5, table 1-2, indicating the number of seismic stations, NSTA). This is due to the small magnitudes and to the wrong estimates of the trial hypocentres which "throw" the values of the first corrected hypocentres after the first iteration somewhere above zero: as a consequence the hypocentres become automatically zero and remain so until the last iteration. (fig.1-10).

(6) The standard error in the depth location for most hypocentres is zero where the depths of foci become zero; the early events of 1929 and 1932 have large standard errors for their hypocentres due to small magnitudes and poor seismic observations which led to large residuals. It is noticeable that comparable small magnitude events since the late 1950's have better hypocentre estimates (SEDEPTH = 5-15 km), because of the growing number of seismic observations (NSTA). (table 1-2).

(7) Standard errors for the epicentres (SELAT and SELON) are equally large when there are few seismic observations and large residuals, but can be reasonably low when the trial epicentre was close to the relocated one and the residuals were small.

(8) There is no apparent correlation between the crustal ($h < 50$ km) and subcrustal events at the Carpathian arc, (fig.1-10) except that on the epicentral map the shallow events are mostly located in a region external to the zone of intermediate focus events.

List of shallow events (h 50 km) at the Carpathian arc, 1928-1965, relocated through Bolt's program
(the entries are from the BCIS and ISC bulletins)

No.	Event	LAT. N o	LON.E o	NSTA	DEPTH km	SELAT km	SELON km	SEDEPTH km	SETIME sec
1	20.05-1929	46.26	26.52	14	30	11.8	3.8	52.5	5.6
2	27.05.1932	41.57	26.39	17	-	60.6	13.2	35.0	3.9
3	02.02.1934	46.44	26.23	19	0	32.3	9.7	0.0	1.3
4	01.11.1936	45.88	26.73	15	0	16.3	4.9	0.0	1.0
5	28.04.1943	45.88	26.96	12	0	16.5	14.5	0.0	1.6
6	12.03.1945	45.82	26.14	27	0	10.3	8.7	0.0	1.1
7	20.07.1955	45.01	27.82	5	0	-	-	0.0	-
8	04.01.1956	45.76	26.32	6	0	4.1	5.7	0.0	0.5
9	08.03.1956	45.58	26.81	4	0	10.9	1.0	0.0	1.3
10	11.03.1956	45.53	26.65	5	0	4.0	5.2	0.0	0.4
11	18.04.1956	46.09	27.86	14	0	7.7	7.8	0.0	0.8
12	04.11.1956	46.12	27.50	5	0	11.1	24.8	0.0	2.2
13	30.04.1957	46.37	27.76	4	0	66.7	74.8	0.0	7.5
14	07.04.1958	45.82	26.37	5	8	2.1	4.1	8.0	0.8
15	31.05.1959	45.85	27.33	106	37	4.5	3.0	5.6	0.5
16	04.01.1960	45.04	26.70	95	33	4.1	2.4	11.5	1.4
17	16.09.1965	46.07	27.01	12	38	7.0	5.6	15.1	0.7

NSTA = number of seismic observations
SELAT = standard error for relocated latitude of event
SELON = standard error for relocated longitude of event
SEDEPTH = standard error for relocated depth of event
SETIME = standard error for the origin-time of event

Table 1-2

Bolt relocation of Carpathian shallow events (1928-1965)

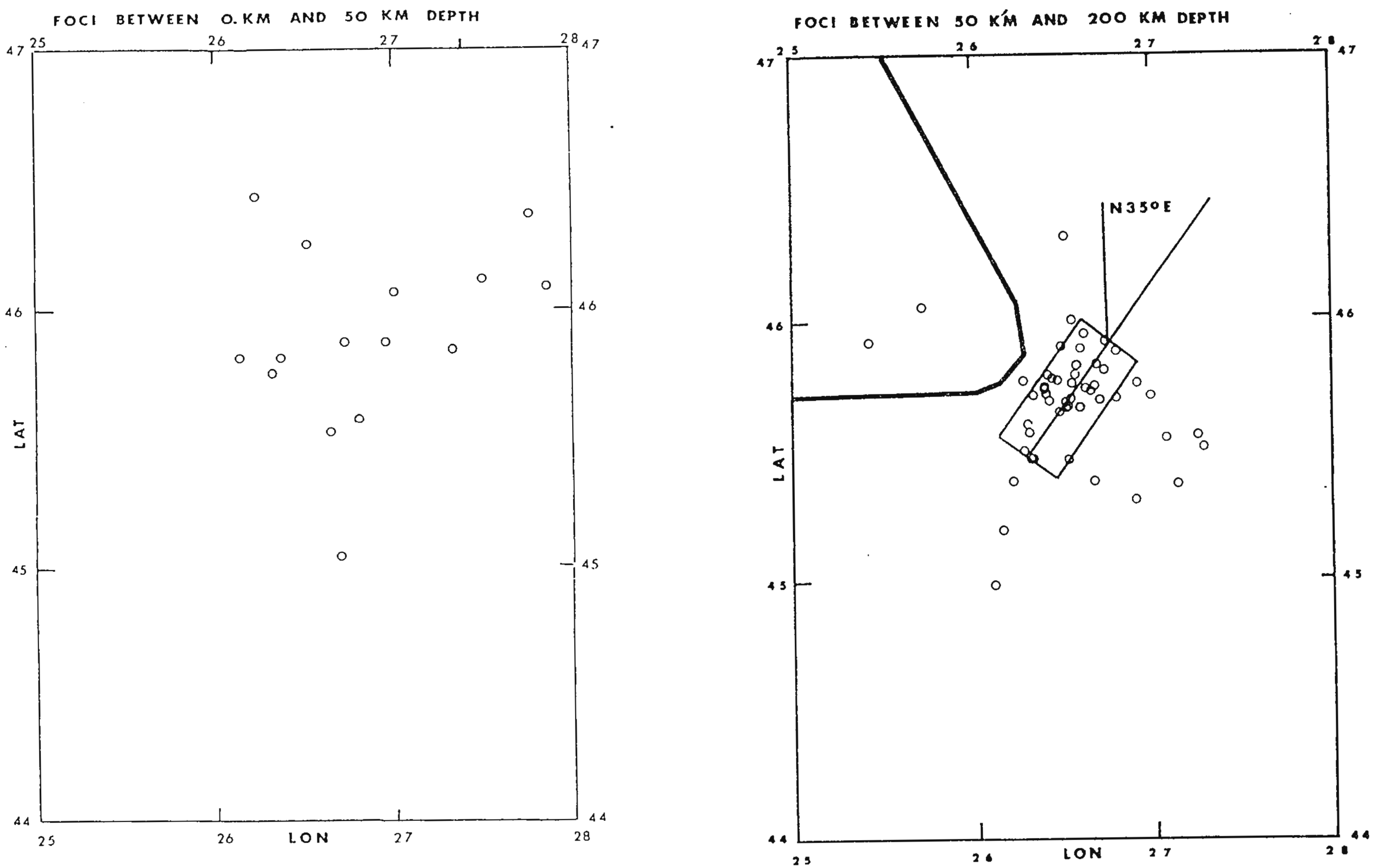


Fig.1-15

Bolt relocation of Carpathian epicentres (1928-1965) (after Roman,1970).

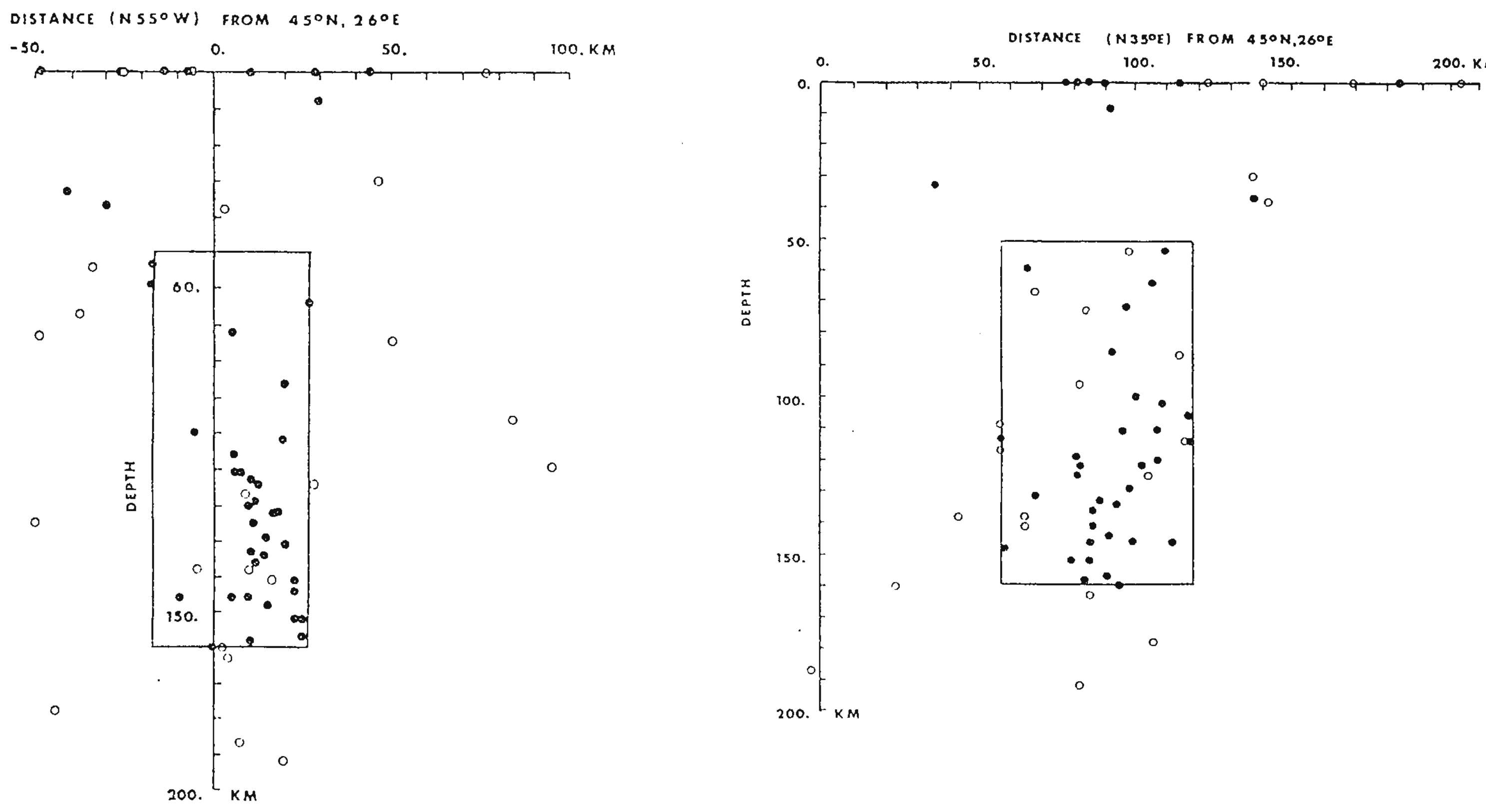


Fig.1-16

Bolt relocation of Carpathian hypocentres (1928-1965)

(after Roman,1970).

Table 1-3

Subcrustal events at the Carpathian arc, 1928-1965 (h 50 km), entries from the BCIS and ISC bulletins

No.	Event	Lat °N	Lon °E	N	Depth km	Selat km	Selon km	Sedepth km	Setime sec
1	23.11.28	46.32	26.52	8	74	15.0	4.6	26.0	0.9
2	01.11.29	45.78	26.44	67	44	6.4	2.9	11.5	0.6
3	29.03.34	45.77	26.47	74	86	5.8	2.1	8.8	0.6
4	13.07.35	45.95	26.62	46	87	9.8	4.0	21.3	0.9
5	17.05.36	45.19	26.15	20	160	24.1	9.5	41.7	1.3
6	13.07.38	45.89	26.60	33	102	7.8	3.2	13.7	0.5
7	05.09.39	45.83	26.69	29	120	9.3	5.0	12.2	0.7
8	24.06.40	45.92	26.74	40	114	5.8	4.1	10.1	0.6
9	22.10.40	45.69	26.42	85	122	4.9	2.2	5.1	0.4
10	10.11.40	45.74	26.63	148	111	6.1	2.7	6.0	0.6
11	08.11.40	45.57	26.31	17	141	10.4	9.2	16.9	1.1
12	11.11.40	46.00	26.55	34	114	11.1	6.6	19.9	1.0
13	19.11.40	45.55	27.25	15	178	19.7	7.5	31.3	1.2
14	23.11.40	45.46	26.53	9	138	21.6	8.9	37.9	1.2
15	13.04.42	44.98	26.10	7	187	45.7	70.4	94.4	9.2
16	07.09.45	45.90	26.49	52	64	5.4	2.6	7.6	0.6
17	09.12.45	45.73	26.66	50	72	7.3	3.5	9.2	0.7
18	03.10.46	45.47	26.33	25	117	13.2	5.1	20.3	0.9
19	03.11.46	45.60	26.30	42	131	7.4	4.2	10.7	0.6
20	17.10.47	45.83	26.58	21	122	9.0	3.3	13.3	0.6
21	13.03.48	45.66	26.59	14	163	16.6	5.7	13.8	0.7
22	29.04.48	45.66	26.51	10	158	11.0	3.2	11.8	0.4
23	29.05.48	45.79	26.57	66	129	6.0	2.7	7.3	0.5
24	26.12.49	45.70	26.55	21	133	11.6	5.1	10.7	0.6
25	16.01.50	45.47	26.32	33	113	8.8	3.3	8.5	0.6
26	20.06.50	45.75	26.40	48	141	6.2	3.2	8.4	0.5
27	14.07.50	45.71	26.99	15	53	7.1	7.3	11.5	0.7

Table 1-3 contd.

No.	Event	Lat °N	Lon °E	N	Depth km	Selat km	Selon km	Sedepth km	Setime sec
28	18.03.51	45.75	26.68	16	146	4.9	3.3	6.2	0.4
29	16.01.52	45.37	27.14	15	73	9.1	11.4	19.5	1.2
30	03.06.52	45.55	27.08	45	54	11.0	6.5	20.2	0.9
31	03.08.52	45.50	26.28	46	148	3.7	2.0	4.2	0.3
32	01.05.55	45.65	26.49	30	125	5.0	4.2	10.1	0.8
33	24.12.55	45.70	26.80	6	100	398.8	785.2	0.0	67.6
34	27.12.55	45.70	26.80	6	100	398.8	785.2	0.0	67.6
35	16.02.56	45.92	25.42	8	109	12.8	20.5	26.3	1.0
36	07.05.56	45.76	26.92	12	146	5.7	8.7	6.7	0.5
37	23.09.56	45.70	26.80	4	100	5.7	8.7	6.7	0.5
38	18.11.56	45.69	26.70	12	160	7.1	5.8	6.9	0.6
39	02.09.57	45.51	27.29	8	125	12.7	27.0	17.0	1.5
40	02.12.57	46.05	25.72	8	96	7.5	10.8	13.2	0.8
41	23.12.57	45.38	26.67	21	59	5.7	5.2	8.5	0.5
42	27.03.58	45.88	26.80	12	106	7.1	6.9	10.1	0.6
43	09.06.58	45.38	26.22	10	138	31.5	17.8	20.8	2.2
44	25.06.58	45.67	26.53	20	146	5.3	4.4	6.6	0.4
45	26.06.59	45.69	26.52	41	136	4.9	3.7	6.1	0.4
46	30.06.59	45.65	26.48	25	119	5.1	3.5	8.0	0.5
47	19.08.59	45.79	26.41	41	157	5.1	3.4	6.3	0.4
48	26.01.60	45.74	26.39	102	152	3.2	1.8	3.7	0.3
49	13.10.60	45.71	26.33	105	152	3.2	1.8	3.7	0.3
50	14.01.63	45.81	26.73	110	111	3.4	1.6	3.8	0.2
51	17.06.64	45.72	26.40	15	192	13.7	10.7	13.1	0.8
52	08.08.64	45.31	26.90	11	67	9.3	15.0	17.6	1.0
53	10.01.65	45.76	26.55	138	134	2.8	1.5	2.7	0.2

2.1.2 Subcrustal events at the Carpathian arc

The revision of earthquake epicentres, focal depths, and origin times using Bolt's program revealed a vertical seismic body in the form of a parallelepiped, 60 km long, 30 km wide and 160 km deep (Roman, 1970, figs.1-15 & 1-16). The epicentral map of intermediate depth events between 1928 and 1965 shows that most of the subcrustal earthquakes occur in a region external to the arc and are contained within a rectangle, 30 km x 60 km, at a tangent to the elbow of the mountain arc (the Vrancea mountains of the E. Carpathians); they are oriented N 35°E (fig. 1-15). The two vertical cross sections through the parallelepiped (figs.1-16) are at right angles to each other and run parallel to the sides of the seismic body. The solid circles mark the best located foci (within 10 km), whilst the open circles mark the foci with larger standard errors.

If one considers the two vertical cross sections through the Benioff zone under the Carpathian arc of Romania, one can make the following comments:

(1) The maximum depth of the seismic activity under the Carpathian arc is 200 km, if one takes into account the less well located foci (marked with open circles), and most certainly the maximum depth could be estimated at 160 km if one takes into account only the best located foci (within 10 km accuracy, marked with solid circles).

(2) The maximum of seismic activity occurs between 100 and 160 km depth.

(3) The abrupt ending of the Benioff zone at 160 km depth

probably corresponds to a low-velocity layer and, if compared with other Benioff zones for intermediate or deep seismic activity, one can see that at about 160 km depth there is either a complete cessation of this activity, or a gap.

(4) Under the Carpathian arc, the spatial distribution of the hypocentres presents a zone of low seismic activity between 30 and 60 km depth.

(5) The verticality of the Benioff zone under the Carpathians is rather an unusual feature when compared to other zones of intermediate depth foci, most of which dip at an angle around 45° (Isacks and Molnar, 1969).

The above comments may be completed with a few remarks regarding the quality of the relocation of subcrustal events presented in table

(6) Between 1928 and 1965, the intermediate depth earthquakes were more frequent than the crustal earthquakes, the subcrustal events representing 75% of the total seismic activity (53 events out of a total of 70). Keeping in mind that the most destructive shocks are located at intermediate depths, it follows that the maximum release of energy corresponds to the intermediate depth seismicity.

(7) The hypocentres tend to be less well located than the epicentres, as is obvious from comparing the columns showing the standard errors for latitude, longitude and depth.(table 1-3). Nevertheless, the standard errors for hypocentres tend to decrease with the increase in number of European seismic stations in the 1950's, since the standard error for focal depth rarely goes beyond 10 km (and this for the smallest

magnitudes only).

(8) The reliability of hypocentres, on which is based the division of hypocentres into two groups marked by "open" and "solid" circles, is determined by the formula:

$$\text{(solid circle)}\ 0 \leq 10 - \sqrt{(SELAT^2 + SELON^2 + SEDEPTH^2)/3} < 0\ \text{(open circle)}$$

where

SELAT = standard error latitude (km)
SELON = standard error longitude (km)
SEDEPTH = standard error focal depth (km)
solid circle = accuracy of hypocentre location within 10 km
open circle = accuracy of hypocentre location without 10 km.

2.1.3 Comparative study of epicentral relocations at the Carpathian arc, using Bolt's and JED methods (fig.1-17).

As we have already pointed out in chapter 2.1, the station corrections are very important when they are close to the epicentre. In the case of the Carpathian seismicity the stations situated in the intra-Alpine basins of Transylvania and Panonia present large residuals, up to + 6 seconds (see fig.1-20) chapter 2.2), due to the large inhomogeneities in the crust and upper mantle, which are caused by the high heat flow in Hungary. It is obvious that the location of small magnitude events at the Carpathian arc relies heavily on these seismic stations with large residuals. When the relocations were made individually (Bolt's program), these residuals could not be entirely corrected, as they are not evenly distributed and

Table 1-4 Comparative table of JED and Bolt relocated events at the Carpathian arc (1928-1965)

NR.	JED			BOLT		
	DATE	LAT	LON	LAT	LON	DEPTH
1	23.11.28.	45.966	26.330	46.32	26.52	74
2	20.05.29	45.812	26.271	46.26	26.52	30
3	01.11.29	45.444	26.305	45.78	26.44	144
4	02.02.34	45.289	25.961	46.44	26.23	0
5	29.03.34	45.401	26.401	45.77	26.47	86
6	13.07.35	45.592	26.510	45.95	26.62	87
7	17.05.36	45.155	26.062	45.19	26.15	160
8	01.11.36	45.551	26.602	45.88	26.73	0
9	13.07.38	45.527	26.530	45.89	26.60	102
10	05.09.39	45.483	26.606	45.83	26.69	120
11	24.06.40	45.515	26.504	45.92	26.74	114
12	22.10.40	45.408	26.343	45.69	26.42	122
13	10.11.40	45.538	26.627	45.74	26.63	111
14	08.11.40	45.213	25.995	45.57	26.31	141
15	11.11.40	45.669	26.451	46.00	26.55	114
16	19.11.40	45.211	27.018	45.55	27.25	178
17	23.11.40	45.171	26.320	45.46	26.53	138
18	13.01.42	44.606	26.087	44.98	26.10	187
19	28.01.43	45.618	26.982	45.88	26.96	0
20	12.03.45	45.493	26.256	45.82	26.14	0
21	07.09.45	45.608	26.506	45.90	26.19	64
22	09.12.45	45.395	26.566	45.73	26.66	72
23	03.10.46	45.235	26.376	45.47	26.33	117
24	03.11.46	45.333	26.222	45.60	26.30	131
25	17.10.47	45.527	26.507	45.83	26.58	122
26	13.03.48	45.409	26.542	56.66	26.59	163
27	29.04.48	45.310	26.186	45.66	26.57	158
28	29.05.48	45.471	26.552	45.79	26.55	129
29	26.12.49	45.403	26.185	45.70	45.79	133
30	16.01.50	45.134	26.233	45.47	26.32	113
31	20.06.50	45.440	26.328	45.75	26.40	141
32	14.07.50	45.524	26.589	45.74	26.99	53
33	18.03.51	45.484	26.494	45.75	26.68	146
34	16.01.52	45.115	27.018	45.37	27.14	73
35	03.06.52	45.325	26.874	45.55	27.08	54
36	03.08.52	45.216	26.164	45.50	26.28	148
37	01.05.55	45.405	26.412	45.65	26.49	125
38	16.02.56	45.668	26.006	45.92	25.42	109
39	18.04.56	45.797	27.590	46.09	27.86	0
40	07.05.56	45.484	26.725	45.76	26.92	146
41	18.11.56	45.444	26.696	45.69	26.70	169
42	02.12.57	46.134	26.394	46.05	25.72	96
43	23.12.57	45.134	26.594	45.38	26.67	59
44	27.03.58	45.568	26.673	45.88	26.80	106
45	09.06.58	45.189	26.130	45.38	26.22	138
46	25.06.58	45.349	26.417	45.67	26.53	146
47	31.05.59	45.580	27.283	45.85	27.33	37
48	26.06.59	45.376	26.125	45.69	26.52	136
49	30.06.59	45.364	26.369	45.65	26.48	119
50	19.08.59	45.468	26.398	45.79	26.44	157
51	04.01.60	44.795	26.726	45.04	26.70	33
52	26.01.60	45.519	26.277	45.74	26.39	152
53	13.10.60	45.406	26.295	45.71	26.33	152
54	14.01.63	45.512	26.709	45.81	26.73	111
55	17.06.64	45.349	26.169	45.72	26.40	192
56	08.08.64	44.939	26.584	45.31	26.90	67
57	10.01.65	45.489	26.515	45.76	26.55	134
58	16.09.65	45.750	26.730	46.07	27.01	38

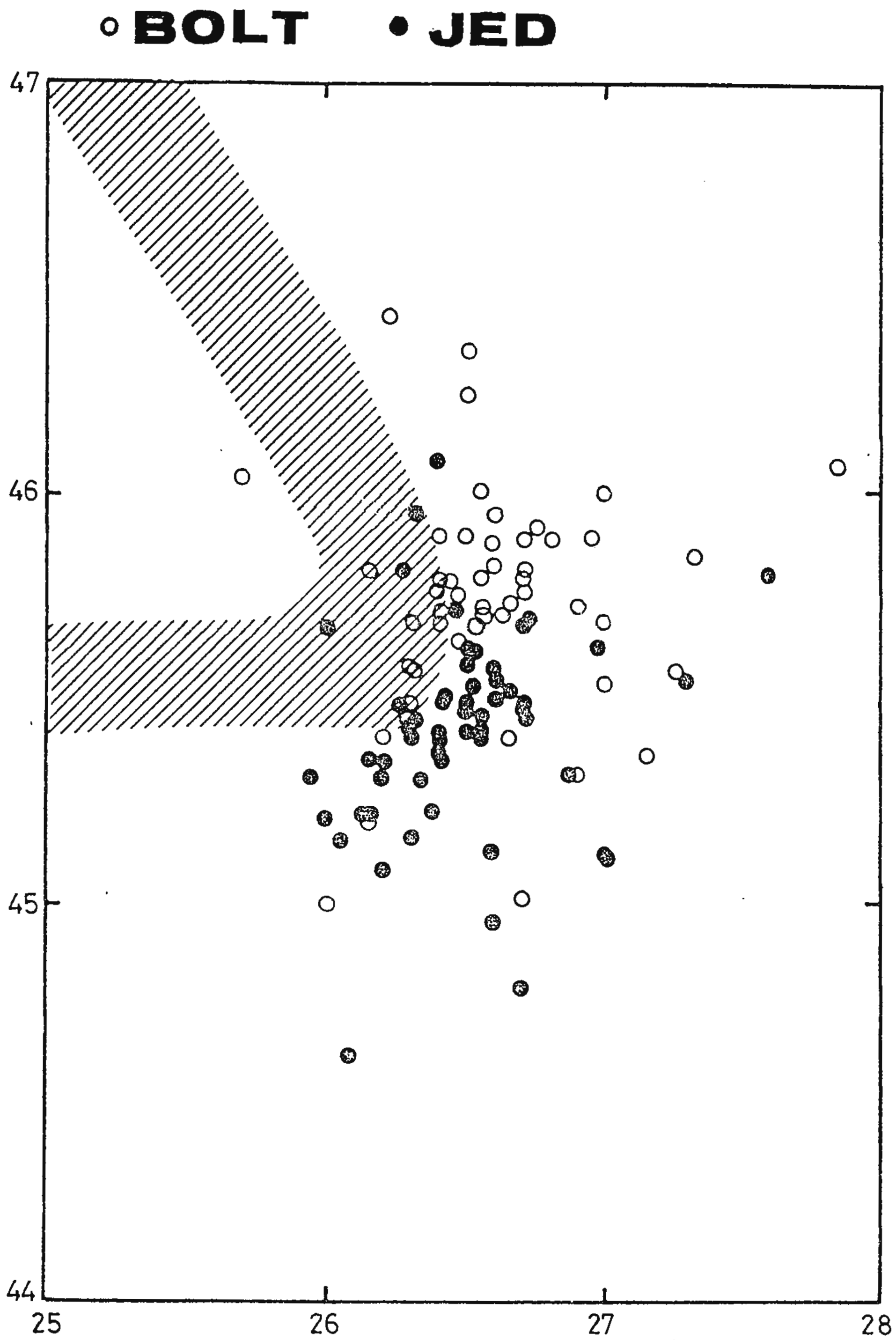


Fig.1-17

Comparative map of Bolt and JED relocated epicentres at the Carpathian arc (1928-1965) (after Roman,1973c).

There is a southward 'migration' of the epicentre location from Bolt to JED. As a whole the JED epicentres appear better clustered at the Carpathian elbow. The precise locations are given in table 1-4, page 93 especially as they are not comparable, even though their distances from the epicentre are the same (see fig. 1-10 in chapter 2.2 and the residual spheres in the appendix). When the relocation is done simultaneously for a group of events this difficulty is overcome, as the average travel-time residual for each individual station is taken into account before the events are relocated; this task is facilitated by the fact that the source of seismicity is almost punctual (at the global scale a Benioff zone like that at the Carpathian arc, of 30 km x 60 km x 160 km, could easily be recognised as such) - so the source bias would in all cases be the same. That is why from the discussion in chapter 2.2 it appears clearly that the cause of the P-travel-time anomalies is under the recording station and not under the source. Consequently, the relocations computed through one method or another show comparatively more discrepancy for the smaller magnitude earthquakes (and probably for shallow events and for events prior to the 1950's) than for the larger magnitude events like the master event of 10 November 1940, which is the largest of the whole group for the period 1928-1965. The exact figures for relocated epicentres are presented in table 1-4 on which the above assertions are made.

Perhaps a more intuitive way of looking at these results appears from the epicentral map in figure 1-11, where the Bolt relocations are marked with open circles and the JED epicentres with solid circles. It immediately becomes clear that:

(i) the spread of the seismic activity along the longitude is greater according to the Bolt locations than according to the JED locations;

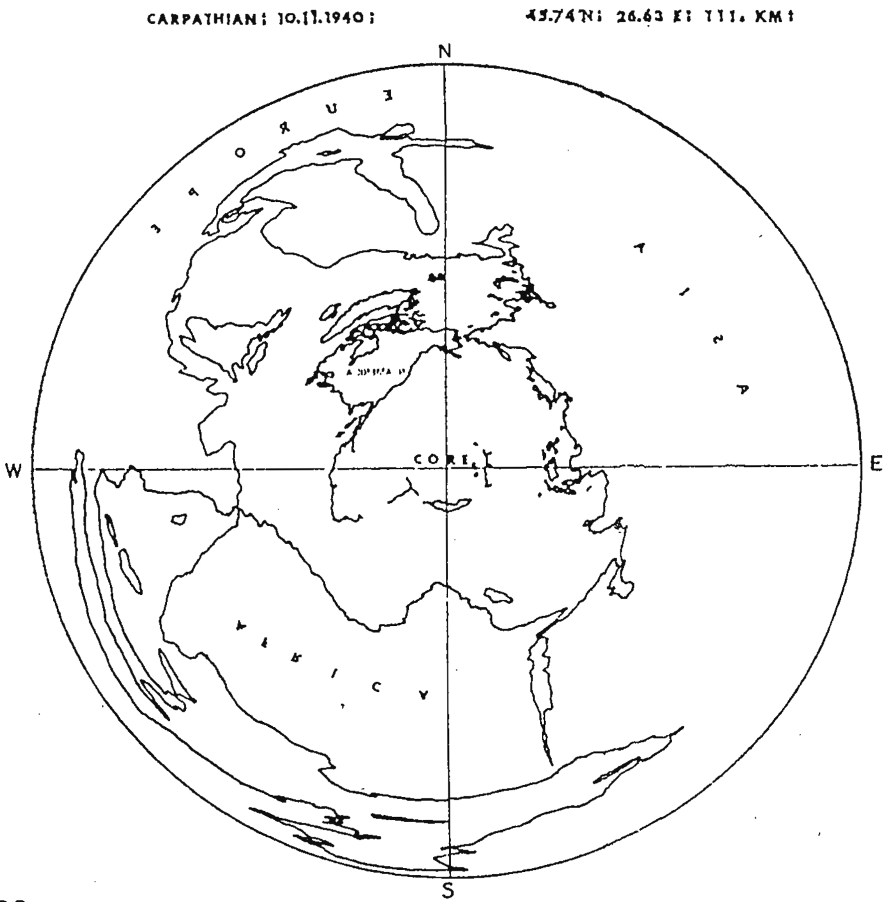
(ii) the concentration of JED epicentres appears more clearly confined to a small zone tangent to the mountain arc than the Bolt epicentres which appear more scattered. (This is also the case in Transylvania, that is in the hinterland, known to be aseismic);

(iii) the "path" of the same epicentre from the Bolt to the JED location seems to be greater in the north than in the south; for example, the Bolt epicentres furthest to the north of the seismic zone tend to have a longer path of migration towards the master event, which is at the Carpathian arc, while the Bolt epicentres which are already close to the master event tend to migrate along shorter paths;

(iv) a path could be as long as 0.5° (latitude/longitude) for the smaller magnitude events.

2.2 Study of the P travel-time residuals in the Carpathians

The revision of 70 Carpathian earthquakes between 1928 and 1965, using Bolt's program (Bolt, 1960), revealed a vertical parallelepiped (60 km long, 30 km wide, 160 km deep) tangent to the Carpathian arc (chapter 2.1). This has been interpreted in the light of Plate Tectonics theory (Roman, 1970)(figs.1-29&1-31) (chapter 5.1); a number of geophysical and geological characteristics of the area adjoining the Carpathians have been recognised as typical of regions affected by a sinking lithosphere (Roman, 1971)(fig.1-30).



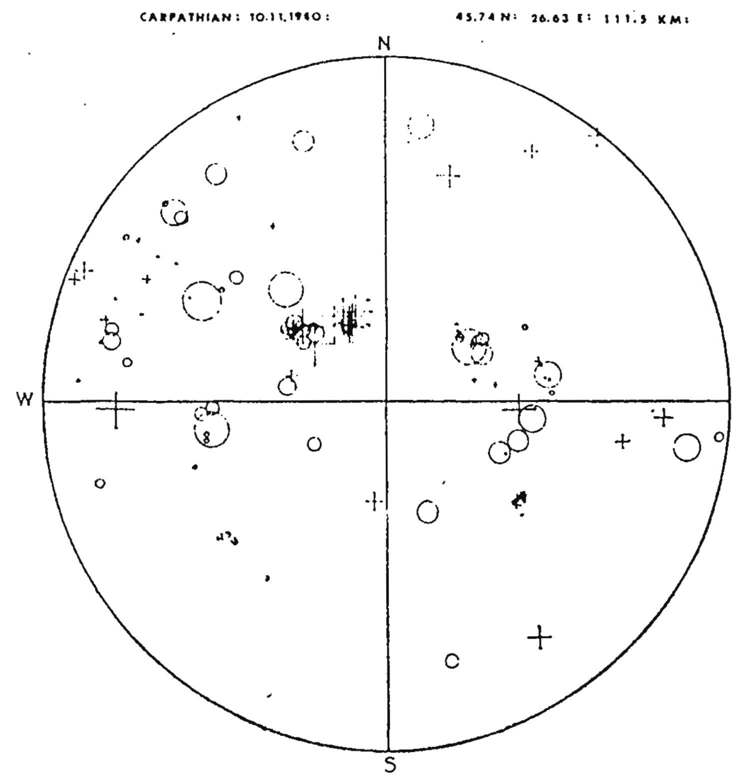


Fig.1-18

P travel-time residual sphere for the Carpathian subcrustal event of 10.11.1940. (after Roman,1973c).

(a) A world's equal-area projection map with the epicentre of the 10.11.1940 earthquake as its centre of projection. Note that the American stations would have little weight on the sphere, while the European, African and Asian stations would bear a greater weight.

(b) Pluses are late arrivals, up to +2.5 seconds, according to the size of the symbol; open circles are early arrivals, to -2.5 seconds (at one second intervals).
For all the other residual spheres see Addendum 1 at the end of volume 1.

For each Carpathian earthquake which has been relocated through Bolt's program, the travel-time residuals of every station have also been computed and subsequently plotted on a focal sphere in equal area projection.(fig. 1-10). As seen from this projection, the P arrivals at the European, Asian and African stations are of crucial importance for relocating the events at the Carpathian arc, while the arrivals from the American stations clearly are of lesser weight.

The main difficulty in studying the residuals comes from the seismic source of the Carpathian arc which seldom produces earthquakes of a magnitude m_B larger than 5.0. Therefore, in the case of smaller magnitude events, a good three quarter of the focal sphere lacks information.

One of the best covered events during the period 1928-1965 occurred on 10 November 1940 (45.74°N, 26.63°E, 111 km depth). Looking at its residual sphere (fig. 1-10) it is apparent that the remotest stations from Asia and North America tend to give fairly large travel-time residuals, due probably to the poor readings of the onset of first arrivals. The fairly even distribution of both positive and negative residuals on the focal sphere is also evident. We would expect, as is suggested in the case of sinking lithosphere (Davies and McKenzie, 1969;f.1-19, McKenzie and Julian, 1971), to obtain a clear distribution of residuals indicative of the orientation of the sinking plate at the Carpathian arc (Az = 35°, Dip = 90°). Yet such is not the case even for this event (10.11.1940, M = 10 - Mercalli scale), which has the largest magnitude of the series (Atanasiu, 1961). Smaller and more recent events have,

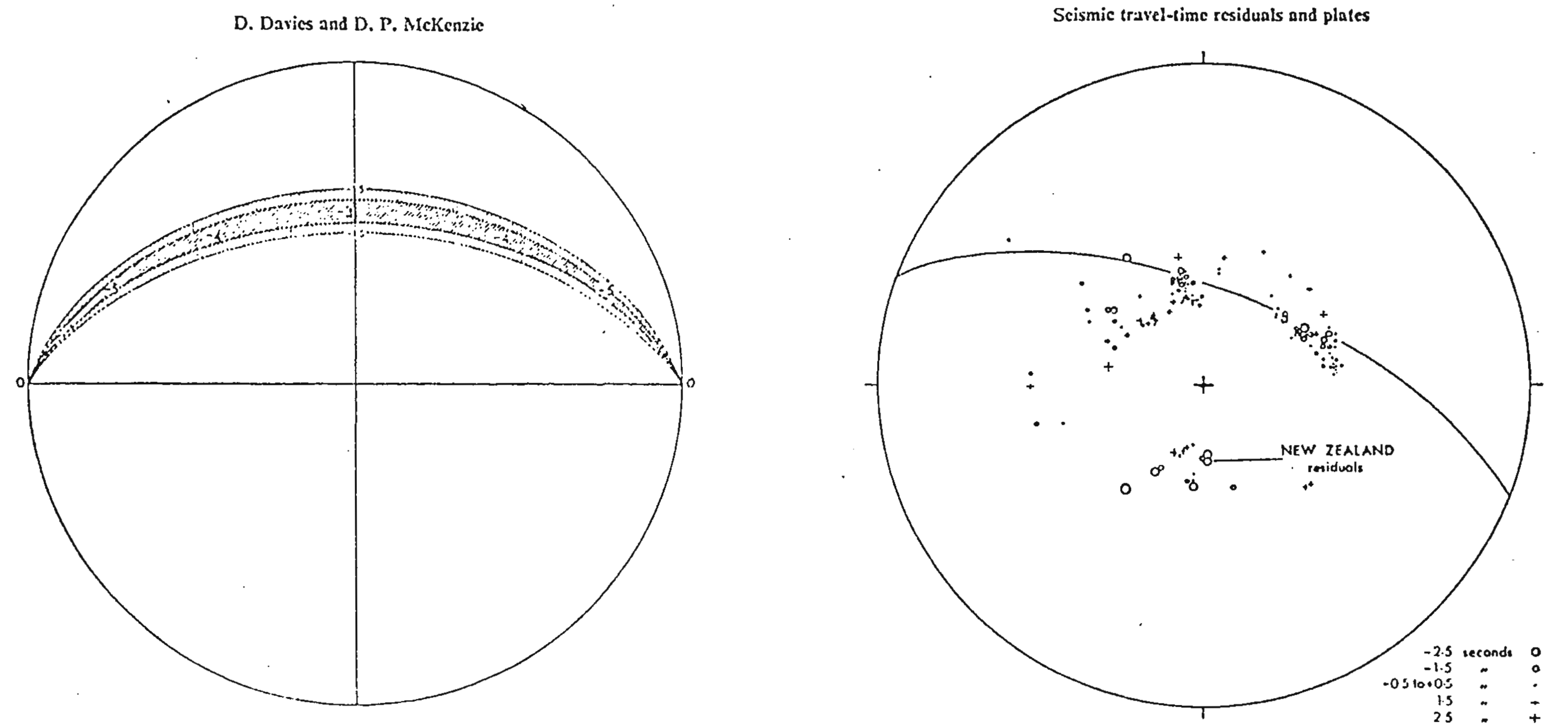


Fig.1-19

Negative P travel-time anomaly shown by lithospheric underthrust on a residual sphere (after Davies & McKenzie,1969).

This shows an anomaly caused by an underthrust along an island arc and was postulated by these authors for all lithospheric underthrusts. If this were true for the Carpathians, then we should expect in all residual spheres a negative anomaly in a N30°E azimuth, which is NOT the case (see Addendum 1, page 115, for illustrations).

however, qualitatively and quantitatively improved entries, yet they equally fail to show the expected 35° azimuthal orientation of negative residuals indicative of the cold plate. The presence of cold slabs was, however, revealed by this method in regions beneath island arcs (the Aleutians, the Kuriles,fig.1-19, Tonga-Fiji-Kermadec). This may suggest that P travel-time anomalies reflect a greater velocity contrast in the region of island arcs than on continents. In the case of the "inactive slab", northwestern United States, there is an equally good contrast between the Pacific oceanic crust and the continental margin. In the case of the Carpathians, the intermediate focus earthquakes occur under continental crust, which is to be found on either side of the sinking slab. So far, by calculating the P travel-time residuals of all stations for each individual earthquake (Bolt's method), one can only say that the residual pattern is caused by velocity anomalies beneath the receiving stations rather than beneath the source.

In order to substantiate this assessment, a parallel method has been used in relocating 58 of the previous 70 Carpathian events, using the same entries from the ISC and BCIS bulletins. This is the Joint Epicentre Determination (JED) program (Douglas, 1967). By using the mean station correction, the JED method has the advantage of locating accurately even the events of smaller magnitude, which appear more scattered when Bolt's method is used (table 1-4 , fig. 1-1, chapter 2.1). After several iterations, the JED program computes for each individual station a mean P travel-time residual from the 58 events. The mean P travel-time residuals

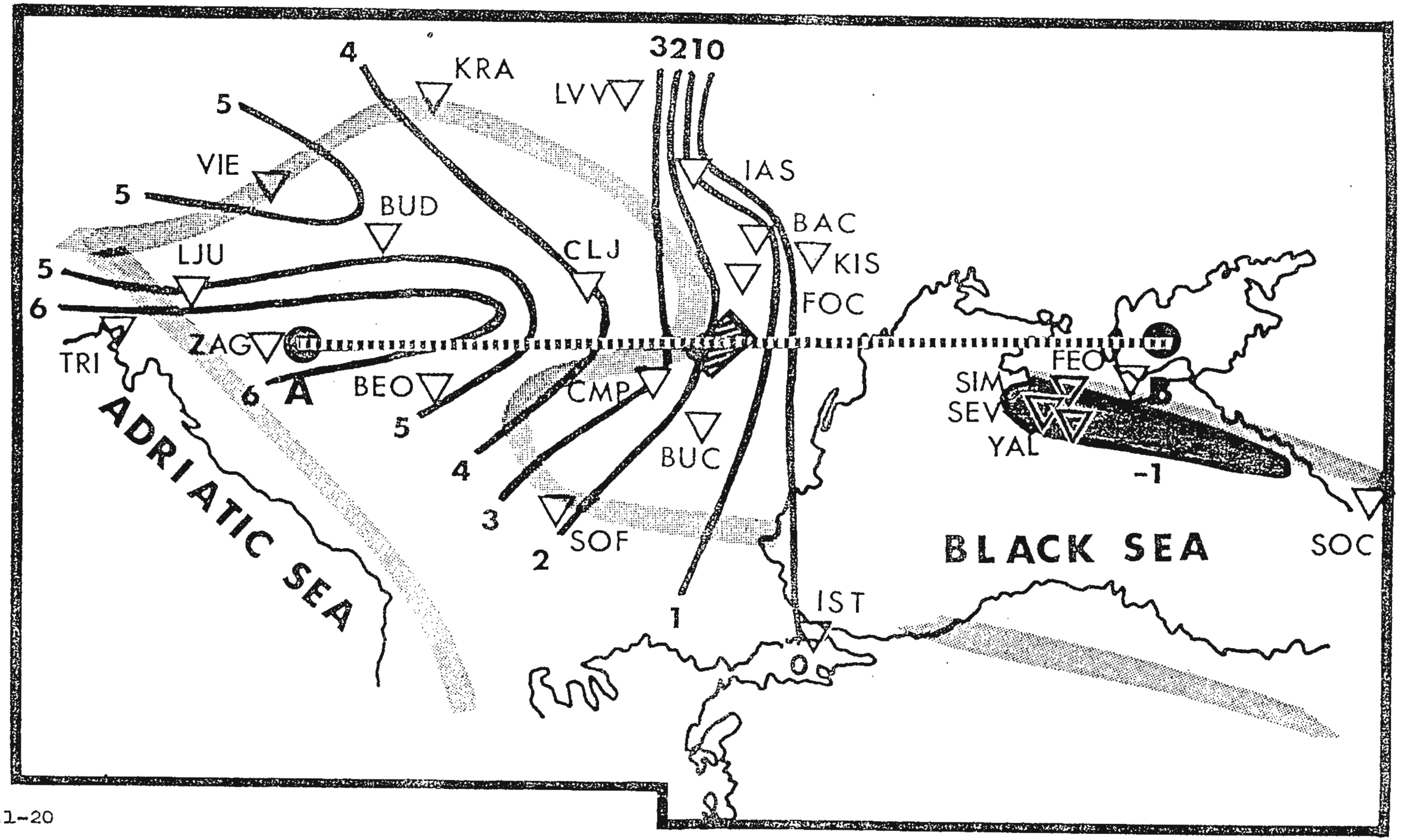


Fig.1-20

Average P travel-time anomaly for 58 Carpathian events (after Roman,1973c). Behind the Carpathian arc, in the intra-Alpine Pannonian basin, there is an anomaly of up to +6 seconds of late arrivals (yellow shaded area), whilst in the Black Sea basin, external to the arc, there is a region of early arrivals, of up to -1 second (blue shaded area). The epicentral zone is presented as a red shaded area, tangent to the Carpathian arc. Numbers represent average residuals in seconds, for 58 events between 1928 and 1965. The open triangles mark the seismic stations close to the epicentral area and noted with the standard three-letter code. The west-easterly 'A-B' profile which crosses the Vrancea region is shown in the fig.1-21.

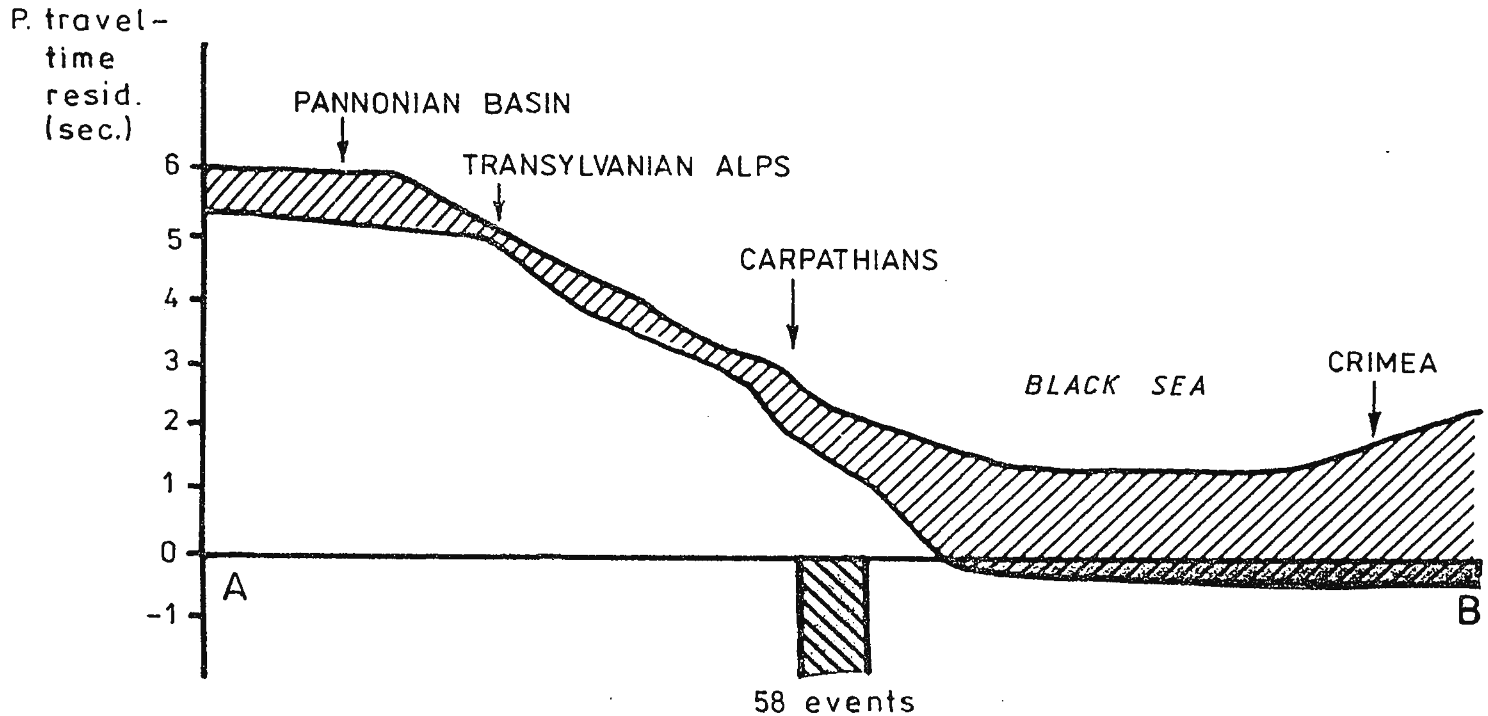


Fig.1-21

West-east profile of P travel-time average values in SE Europe (after Roman,1973c). The shaded area represents the difference between the first and the fourth iteration of the JED program: the difference is obviously bigger in the Black Sea basin, as there are fewer seismic stations than in the Pannonian basin. West of the Carpathian underthrust (marked in red) is the zone of late arrivals (up to +6 seconds) of the Pannonian basin (yellow shading). East of the underthrust is the zone of early arrivals (-1 second) within the Black Sea basin (blue shading).

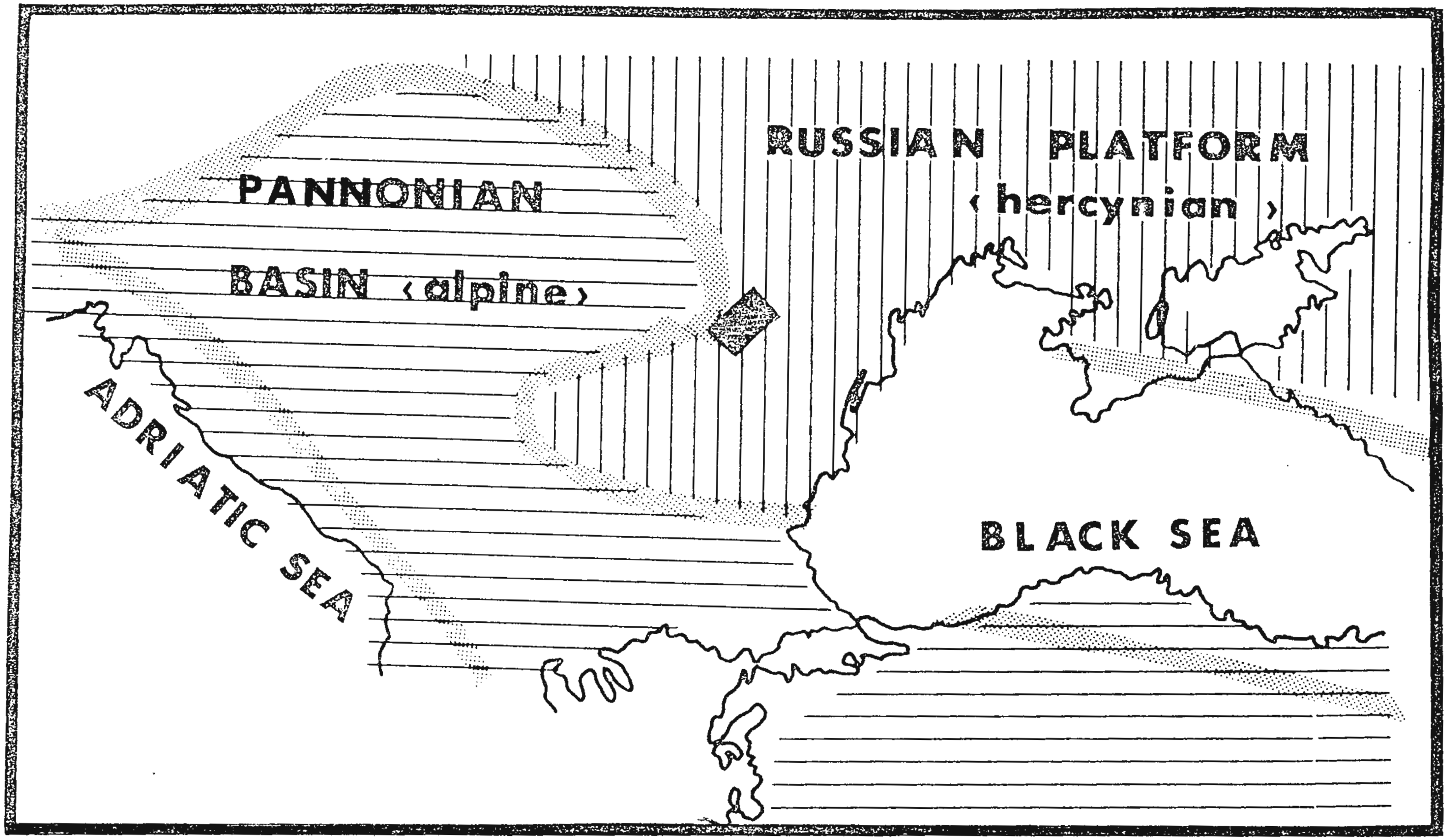


Fig.1-22

Alpine and Hercynian basement in SE Europe (after Roman, 1973c).

The young Alpine basement of the Pannonian basin corresponds to the zone of late arrivals. The old, Hercynian basement, north of the Black Sea, corresponds to the early arrivals. The red shaded rectangle marks the Vrancea underthrust.

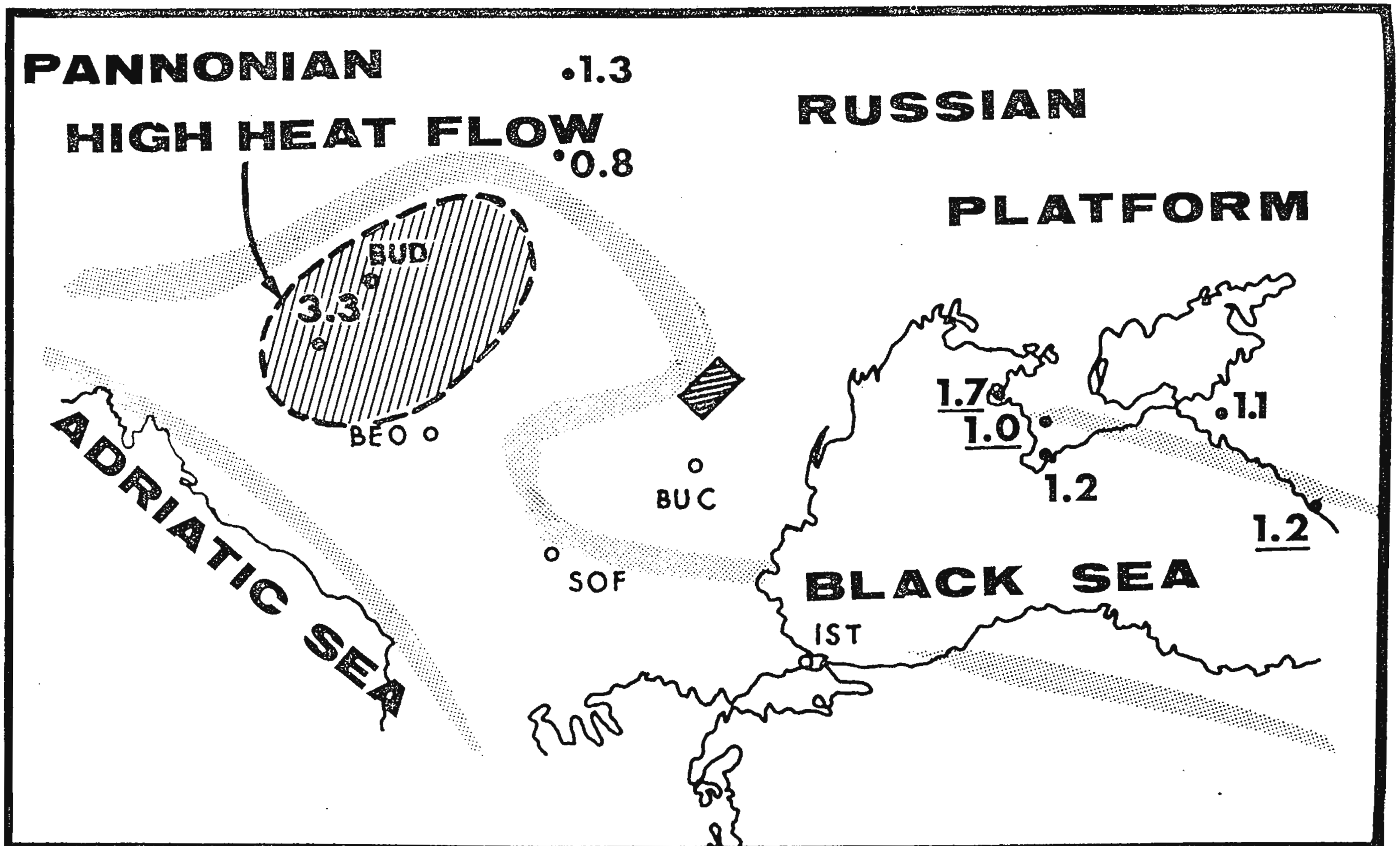


Fig.1-23

Some heat flow values in the Pannonian and Black Sea basins (after Roman,1973c). The high heat flow in Hungary (shaded area) corresponds to the area of Alpine basement (fig.1-22) and late P travel-time residuals (fig.1-20). The normal and low heat flow corresponds to Hercynian basement and early arrivals. The Vrancea lithospheric underthrust is marked with a solid rectangle. Underlined figures are average heat flow values (h.f.u.).

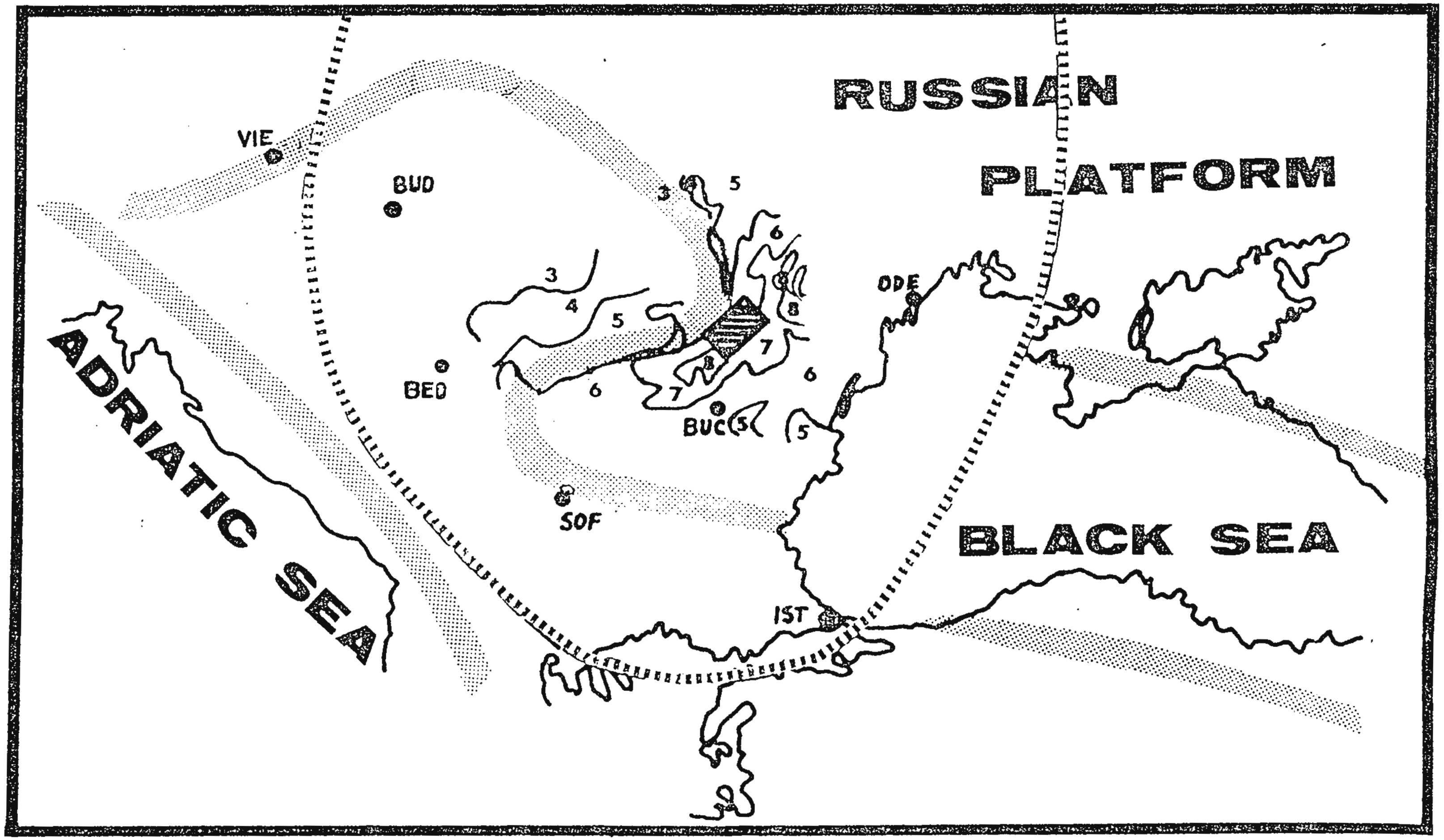


Fig.1-24

Isoseismals of the 10.11.1940 earthquake (after Atanasiu,1961). The Vrancea underthrust is marked with a solid rectangle. Numbers represent the value of the isoseismals on the Mercalli scale. The large area on which the earthquake was felt, from Budapest (BUD) to Istanbul (IST) and up north to Leningrad was marked with a red dotted line. The isoseismals follow the sub-Carpathian trough and are generally of the same shape as the pattern of isovelocities (fig.1-9): they can be correlated, in the region close to the epicentre, to the thickness of the packet of sediments.

for stations within 1200 km of the source have been plotted to cover the area between the Panonian Basin and the Caucasus; subsequently a map of the P travel-time anomalies has been drawn (fig. 1-20).

A cross section of the travel-time anomaly from the Panonian Basin towards the Black Sea, through the Carpathian arc, shows a steep gradient (5 seconds/1000 km) over the sinking slab. On the western side of the sinking slab, in the Panonian Basin, the residuals are between +6 seconds and +2 seconds, while on the eastern side, in the region external to the Carpathian arc, the residuals vary between +2 seconds in the Carpathian foredeeps and -1 second in the oceanic type of crust of the Black Sea basin (fig. 1-21).

This picture correlates remarkably well with the tectonic (Yanshin, 1966), isoseismal (Atanasiu, 1961) and heat flow (Lubimova and Polyak, 1969) evidence for southeastern Europe. On the one hand, there is the intra-Carpathian (Panonian) Basin, having a young Alpine basement (fig. 1-22), a high heat flow (fig. 1-23) and an absorption area (fig. 1-24) which corresponds to late arrivals (+6 secs to +2 secs); on the other hand, there is the region external to the Carpathian arc, having an older basement (Hercynian), a normal and low heat flow, and a highly transmitting area, which corresponds to early arrivals in the zone of the Black Sea oceanic crust.

Herrin and Taggart (1968) point out that mean station corrections for P travel-times are positive in the tectonically active areas and negative in the more stable regions. This is indeed verified by the pattern of P travel-time at the Carpathian arc.

Conclusions

The P travel-time residuals of stations for each individual event computed through Bolt's program do not show an anomalous region for the sinking slab under the Carpathian arc.

The mean P travel-time residuals, computed (JED) from 58 events for stations within 1200 km from the seismic source, show late arrivals (+6 secs to +2 secs) for the Panonian Basin and early arrivals (-1 sec) for the Black Sea Basin, with a steep gradient over the sinking slab in the region of the Carpathian arc. The travel-time anomaly correlates well with the type of basement as well as with the heat flow and isoseismal pattern in southeastern Europe.

It is suggested that the velocity anomaly is due to causes beneath the station rather than beneath the source.

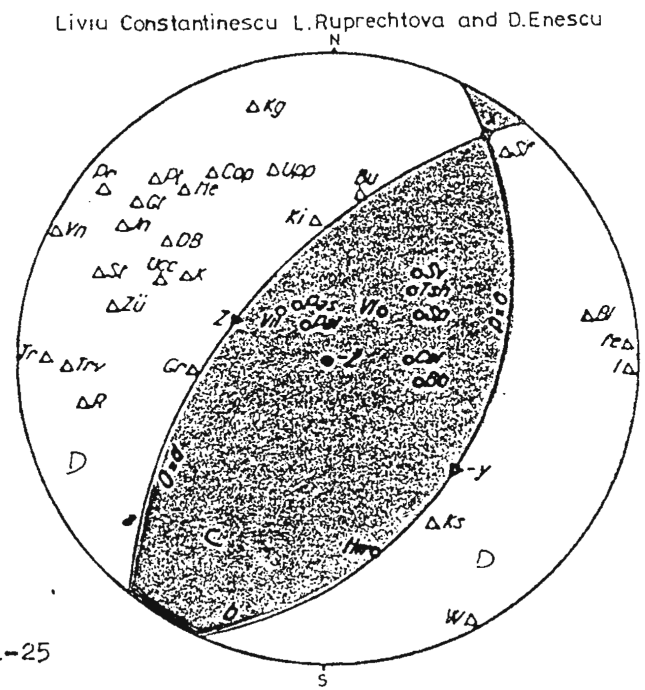
2.3 Focal mechanisms and P and T axes

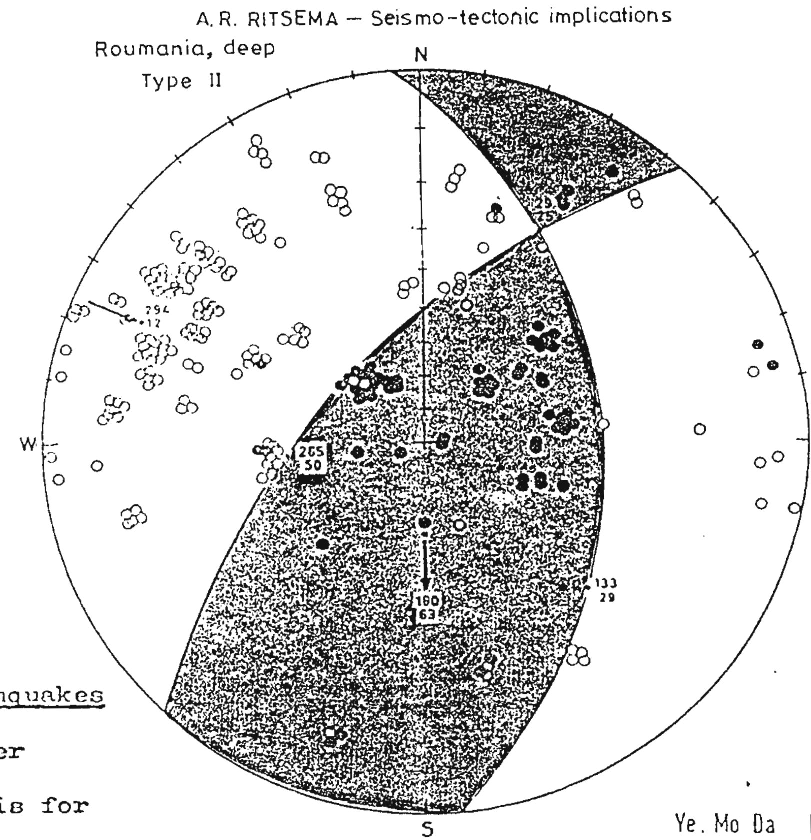
Since the establishment of the World Wide Standard Seismic Network (WWSSN), no large enough earthquakes have occurred in the Vrancea region to enable us to plot reliable focal mechanisms. As can be seen from figure 1-18 in chapter 2.2, the African and Asian seismic stations on the focal sphere are essential for an even distribution of the input data. It is obvious that no reliable focal mechanism could be obtained for any Carpathian event of magnitude m_B smaller than 5.0. A solution would prove almost impossible for the older events, such as the great earthquake of 10 November 1940, because most of the old seismograms have been destroyed.

Some Carpathian mechanisms for the smaller and more recent events have been published by Constantinescu et al. (1966) (fig.1-25) and Ritsema (1969), but these must be considered with caution, for the quality of the input data is questionable: both Constantinescu and Ritsema used onset polarities, not from their own direct readings of the seismograms, but from the readings of a variety of people at the seismic stations concerned. The practice resulted in important errors in the input. Ritsema admits that his individual mechanisms are poor, so he proposes "average mechanisms" for groups of events. In fact, his "type II" mechanism corresponds to what we would expect for the subcrustal shocks of Vrancea. We know already from chapter 2.1 that Bolt's relocation shows an orientation N 35°E of the slab. As a consequence we would expect a thrust focal mechanism with the nodal planes roughly in the 35° azimuth (fig. 1-25).

The focal mechanisms of intermediate earthquakes show the compressional P axis very close to the horizontal (fig. 1-26) and perpendicular to the vertical slab. The tensional T axis (fig. 1-26) is remarkably well contained in the plane of the slab. This result suggests that the slip is caused by the gravitational force of the lithosphere itself.

By comparing the situation with the study made by Isaks and Molnar (1969), we can immediately see that the Carpathian intermediate earthquakes show similar characteristics to those of the intermediate shocks under most of the island arcs (fig. 1-27).





Ye.	Mo	Da	Depth
29	11	01	160 km
40	06	24	115 km
40	10	22	130 km
40	10	22	150 km
40	11	10	150 km
40	11	10	140 km
40	11	11	150 km
45	09	07	100 km
48	05	29	150 km
35	07	13	160 km

Fig.1-25

Focal mechanisms for the Carpathian subcrustal earthquakes

(a): (after Constantinescu et al.,1966); (b): (after Ritsema, 1969). Constantinescu's focal mechanism is for the event 22.10.1940 (our event nr.9 in the table 1-3, page 65, and in the addendum 1 for the residual sphere) and presents a thrust oriented N30°E which is precisely the orientation of the Benioff zone, relocated through Bolt's program (fig.1-15). Ritsema's solution represents an average thrust mechanism for 10 subcrustal events, including the large 10.11.1940 earthquake. The mechanism is similar to Constantinescu's, with a slightly larger strike-slip component.

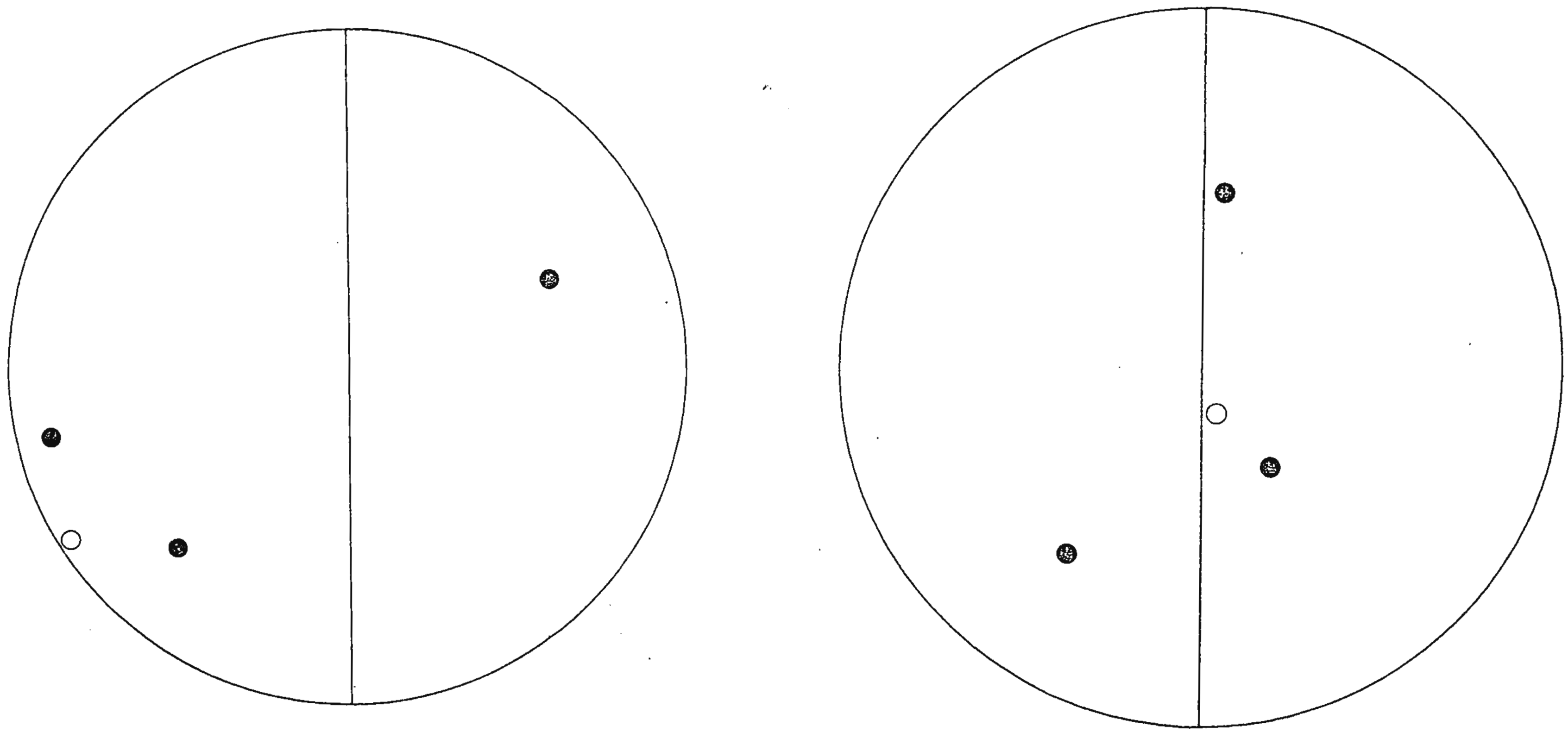
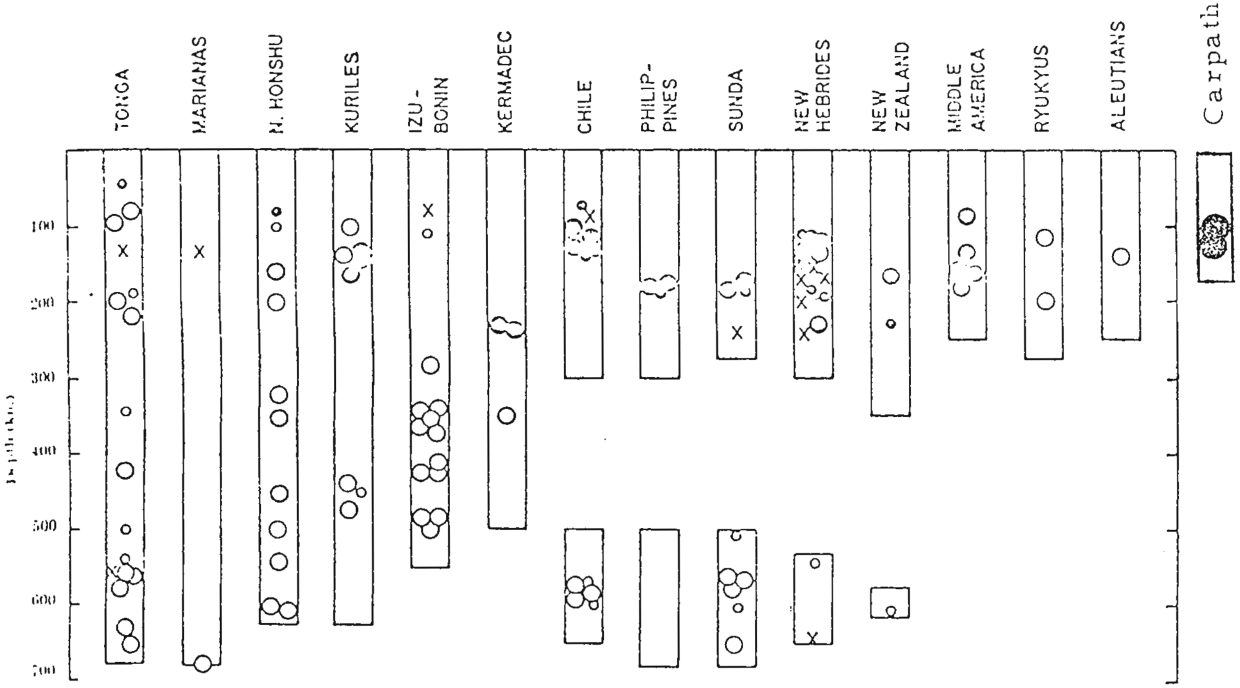


Fig.1-26

Compressional and tensional axes of subcrustal earthquakes, relative to the plane of underthrust at the Carpathian arc (after Roman,1970).(a)The P axis is horizontal and perpendicular to the plane of the sinking plate.(b)The T axis is vertical and contained in the plane of the slab. Solid circles represent averages presented by Ritsema (1969) and open circles are the axis of the event 01.04.1960 after Constantinescu(1966).



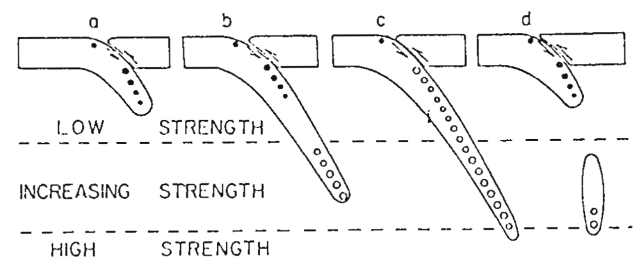


Fig.1-27

<u>Compressional and tensional axes within the sinking lithosphere for various Benioff zones</u> (after <u>Isacks & Molnar</u>,1969).

(a) The Carpathians have been added as a 15th region to the ones already studied by the authors. It is striking to see the similarity between the Vrancea and the Middle America region, as tensional axes are contained within a comparable depth of underthrust.

(b) The Carpathians would fit the case 'a' of this model, except for the angle of the underthrust.

C. interpretation

CHAPTER 3

Seismotectonic Interpretation of the Carpathians

There are three unusual features in the Carpathian seismicity which we shall attempt to explain in this chapter by means of plate tectonic interpretation:

(1) the existence of a nest of earthquakes at intermediate depths, under an intra-continental mountain arc;

(2) the confinement of the Benioff zone to a 60 km horizontal front at the elbow of the Carpathian arc;

(3) the verticality of the Benioff zone.

The first aspect is unusual because, with the exception of the Hindu Kush mountains, all other intermediate and deep seismic zones occur under oceanic trenches, at the limit between an oceanic and a continental type of crust. The intermediate depth earthquakes at the Carpathian arc have continental crust on either side of the mountain arc and the closest portion of oceanic crust is actually found in the Black Sea some 250 km to the southeast.

The second aspect is the spatial limitation of the Benioff zone to a 60 km horizontal front tangent to the mountain arc, when it is known that similar seismicity at intermediate depths occurs under oceanic trenches following the whole extent of an island arc or orogenic trend.

Finally, the verticality of the Carpathian subcrustal nest of foci is unusual in the sense that most of the existing Benioff zones dip at an angle varying between 30° and 60° from the horizontal.

In conformity with the Plate Tectonics hypothesis we assume that the seismic body under the Carpathian arc is part of a lithospheric plate (the Black Sea plate) which comes from the southeast and descends vertically (Roman, 1970).(fig.1-28).

In chapter 3.1 we shall describe the plate boundaries at the Carpathian arc, present physical and geological two-dimensional models in chapters 3.1.1 and 3.1.2 respectively and discuss the limitations of these models in chapter 3.1.3. A speculative viewpoint as to a possible evolution of plates in SE Europe since the Alpine orogenesis will be presented in chapter 3.2.

3.1 Plate boundaries at the Carpathian arc

There are several seismotectonic elements defining a plate, which is understood to be a piece of rigid lithosphere whose boundaries are outlined by seismic belts.

(1) First of all the concept of "rigidity" implies the absence of seismic deformation within the boundaries of a lithospheric plate, if we are to go on calling it a plate.

(2) Secondly the boundaries should be seismically active along oceanic ridges and trenches, major crustal faults and ophiolitic belts.

(3) Thirdly the seismic activity along the boundaries should be confined to very narrow strips (i.e. at the global scale the epicentre distribution should be unidimensional as opposed to being scattered over wide areas).

The concept of rigidity is important because it permits us to treat the plate as an entity, whose movement can thus be described as that of a cap on the surface of a sphere; as a consequence of Euler's theorem we can express the movement of the plate as a rotation about some axis through the centre of the sphere.

The definition of plate boundaries and its corollary, the recognition of a given seismic belt as a plate boundary, is equally important because the relative motion between plates is taken up along such boundaries. It is along these boundaries that the plates are created along oceanic ridges, destroyed under trenches, or slip past each other.

Until recently it was believed that the Carpathian seismicity occurred within the Eurasian plate and this idea still lingers on in present-day literature on Plate Tectonics. This author mentioned for the first time (Roman, 1970) the possibility of the lithospheric underthrust at the Carpathian arc being part of a Black Sea plate, whose boundaries he defined at the 12th Luxemburg Meeting of the European Seismological Commission (Roman, 1971) (fig. 1-28). This means that the Eurasian plate had to be carved up and a new plate, the Black Sea, defined. When it comes to the definition of plate boundaries across continental crust, this practice of carving up large rigid plates into smaller ones is particularly attractive, because it eliminates the possibility of seismic deformation occurring within plates. Consequently we have a greater number of small rigid plates, as shown by McKenzie.(1972) and Nowroozi (1972).(fig.1-34). The usefulness of small plates is, however, debatable (Roman, 1973b), when one is concerned with global tectonics, and therefore this author is particularly cautious about the definition of any new plate and its importance.

Would the Black Sea plate qualify for the status of a lithospheric plate and, if so, what would be its boundaries?

Certainly, the southern boundary, which is the north Anatolian fault, and the eastern boundary, which is the Caucasus, are both well defined by seismically active faults; the Black Sea plate has also some of the oceanic crust which is "desirable" for a plate and most of the basin is free from seismic deformations, which accounts for the required rigidity. The northern boundary could be described by a discontinuity which crosses the Azov Sea and the Crimea from east to west, to join the Carpathian arc of Romania (Yanshin, 1966). But this line is seismically rather inactive, both in frequency and magnitude, as no destructive shock has ever been recorded in historical or modern times; in more recent years, no earthquake has been large enough to allow the construction of a reliable focal mechanism. This has great disadvantages as no slip vectors could be deduced to suggest the relative movement of the Black Sea plate with respect to the Eurasian plate, apart from the slip vectors at the Carpathian arc, along the north Anatolian fault and the Caucasus; however, these are not sufficient. It is very difficult to close up the boundary of the plate through a line which should ideally unite the Carpathian's 60 km front of subduction zone with the westernmost end of the north Anatolian fault.(fig.1-28).There are indeed some basement discontinuities in Bulgaria (the Tvardica fracture, for example), but they are seismically too inactive

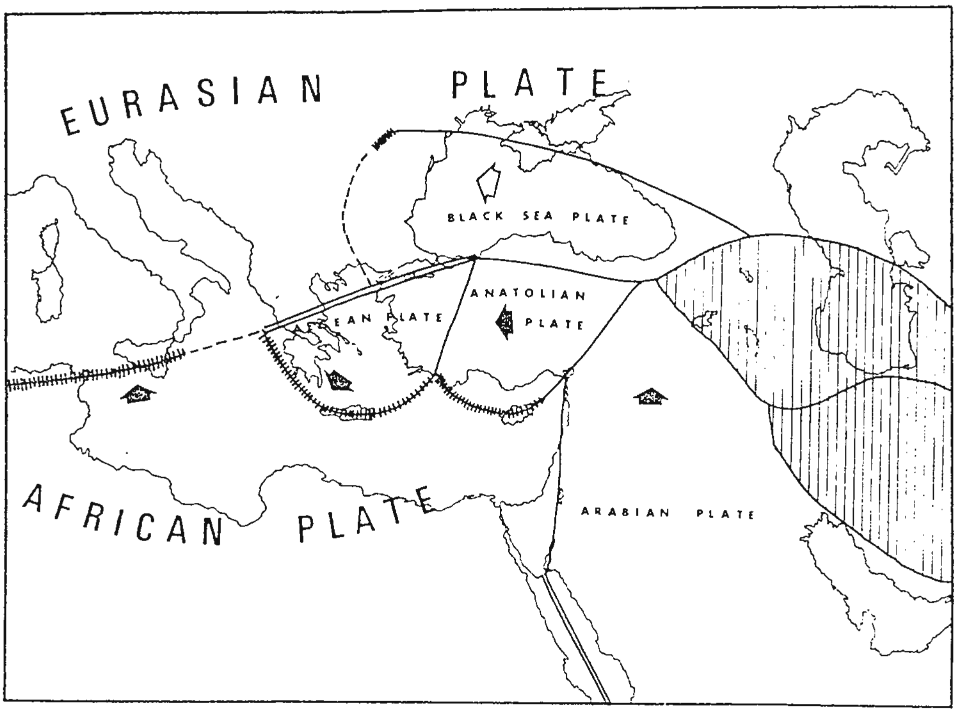


Fig.1-28

Plate model for the Black Sea and E Mediterranean (after Roman,1971)

A comparative model of plates in SE Europe is found in fig.1-34 and in the selection of publications in the pocket of the end of volume 2 (Roman,1973b).

The plate boundaries are marked by faults (solid lines), ridges (double solid lines) and trenches (crossed solid lines).

Uncertain boundaries are marked with dotted lines (sub-plate).

The shaded area represents an active seismic region (buffer plate).

Solid arrows show the relative movement of plates withe respect to Eurasia and the open arrow the uncertain relative movement of the Black Sea sub-plate.

to qualify them for a plate boundary. The western boundary of the Black Sea plate remains an unsolved problem, unless one considers the whole region as a "sub-plate" (Roman, 1973b), about which we shall say more in chapters 3.1.3 and 3.2. Perhaps at this stage we can assert that there is no physical or geological evidence for a western boundary to the Black Sea plate, as proposed by McKenzie (1972b)(fig. 1-34).

3.1.1 Physical model of plates in the Carpathian region

The geometrical distribution of subcrustal earthquakes allowed us the definition of the subduction zone under the Carpathian arc, which for a horizontal front of 60 km is part of the Black Sea boundary. Other sections of the plate's boundary have been similarly defined by observing the strips of crustal events in northern Anatolia, the Caucasus and the Crimea. (fig.1-28).

From the tectonic point of view the north Anatolian fault is a right-handed strike-slip fault, the details of which are known in some detail (Ambraseys, 1970). Along the Crimean and the Caucasus front the boundary is formed by thrust faults (McKenzie, 1972b).

The Deep Seismic Sounding (DSS) in Romania and the Black Sea basin has provided additional information about the structure of the crust within the Black Sea plate and about the buried geometry of the faults considered to be plate boundaries. There, where available, the focal mechanisms would also give a clue as to the type of boundaries (McKenzie, 1972b). Despite the DSS observations we reviewed in chapter 1.3.3, we cannot speculate much on the question of the possible western boundary of the Black Sea plate, which we left open. There might be, though, an area which should be interesting to consider: this is between the Carpathian subduction zone and the Crimea. There the DSS revealed a major crustal discontinuity, buried under the thick packet of sediments, which looks like a thrust fault, running ESE-WNW and suggesting that the southern bloc, which is part of the Black Sea plate, underthrusts the Eurasian plate (Enescu et al., 1972). We cannot at this stage state what the seismic slip along this fault, called the Capidava-Çanara fracture line, is. Other information as to the physical structure of the Black Sea plate refers to the type of crust and suggests that most of the oceanic crust underwent a process of continentalisation which today is found in various stages of completion, at least judging by the sequence of discontinuities (packet of sediments, granitic layer, basaltic layer) (fig. 1-13). This would help us to construct a first fairly simple physical model of plates at the Carpathian arc, by presenting a series of vertical cross sections of the lithospheric underthrust. This two-dimensional model is oriented NW-SE and, for a start, it helps us to understand the simpler processes of the plate evolution, before we can present a more realistic geological model, in chapter 3.1.2. My first model (Roman, 1971) presented an evolution of the plates since the Jurassic (fig. 1-29), that is the time of the opening of the Atlantic. It showed the lithospheric underthrust being in a vertical position from the very beginning, which may not necessarily be true, at least

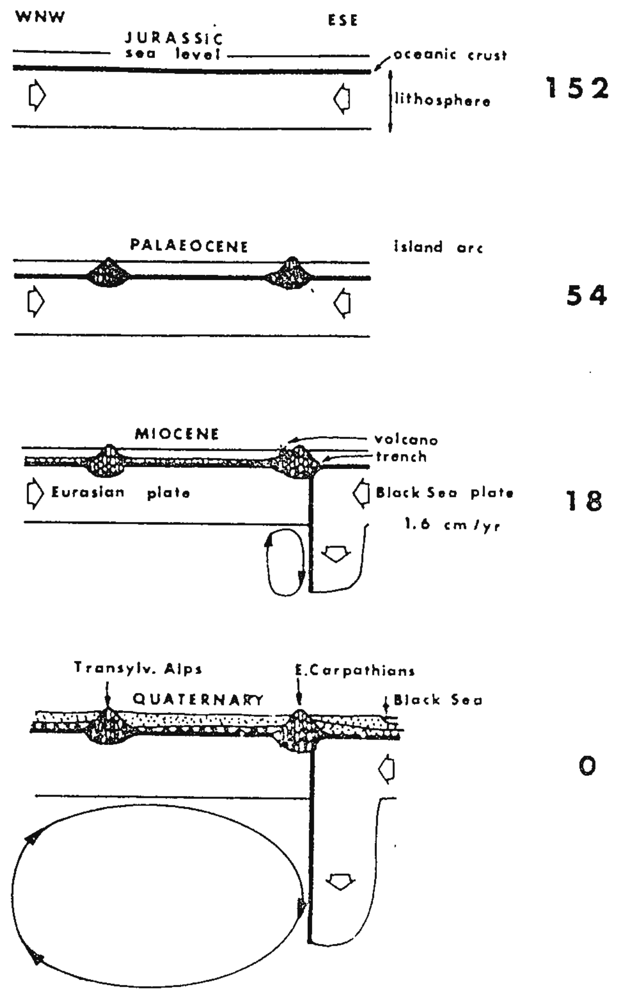


Fig.1-29

Physical model for plate evolution at the Carpathian arc of Romania (after Roman,1971). This mainly speculative model intuitively siggests the relationship between the lithospheric underthrust under the Vrancea mountains and the high heat flow in Hungary, which speeded up the process of continentalisation behind the Carpathian island arc. The shape of the convective cell is also intuitive.

from the geological point of view. The advantage of the model lies, however, in the fact that it can justify the relationship between the underthrust of the cold lithosphere under the Carpathian arc and the presence of high heat flow in Hungary. The idea is that the cold lithosphere going down into the mantle gives rise to a convective cell which produces the high heat flow in the Panonian basin. To get an idea of the order of magnitude of energy transfer caused by a down-going slab of this size, let us consider the formula suggested by McKenzie and Sclater (1969) for heat loss caused by sea-floor spreading and apply it to the sinking lithosphere under the Vrancea mountains:

$$H = \rho CL dv (T_1 - T_0),$$

where

H = heat loss transfer through the sinking of the cold lithosphere

ρ = average density of the lithosphere

C = specific heat

d = horizontal length of the sinking lithosphere

L = thickness of the slab

v = minimum average sinking rate

$T_1 - T_0$ = heat transfer.

Then the substitution of

ρ = 3 g/cc

$L = 3.0 \times 10^6$ cm

$C = 0.25$ cal/g^oC

$d = 6 \times 10^6$ cm

$$v = 1.6 \text{ cm/yr}$$

$$T_1 - T_o = 550^\circ C$$

gives a heat loss $H = 1.2 \times 10^{16}$ cal/yr

or else $H = 5.0 \times 10^{23}$ erg/yr

which is greater by a factor of two than the average energy released through earthquakes, over the period 1937-1962 (Constantinescu and Enescu, 1964). The values for L and d are found from the estimate of the Benioff zone after the relocation of the Carpathian earthquakes; v, the minimum average rate of sinking lithosphere, is inferred from the 160 km vertical length of the underthrust over the past 10 my.

The above exercise enables us to get an idea of the order of magnitudes involved in the heat transfer due to the lithospheric underthrust at the Carpathian arc and to see whether a physical model like the one we proposed could be regarded as realistic or not. It results that the cold down-going slab at the Carpathian arc could account for the high heat flow in the Panonian basin and its corollary, the process of continentalisation of the Miocene oceanic crust which once existed in that basin.

As we shall see from the geological model in chapter 3.1.2, the Carpathian mountains started as an island arc whose oceanic trench destroyed part of the Tethys ocean floor: the present lithospheric underthrust is only a relic of the former Tethian floor. The process of continentalisation already mentioned, which started concurrently with the beginning of the underthrust, can be revealed on the sole basis of physical observations (DSS) even prior to our constructing a more complex geological model, this proved to be a great advantage for the physical model in this chapter.

Comments on the physical model of plates at the Carpathian arc

This model, based on physical observations, allows the understanding of the following characteristics of plates at the Carpathian arc:

(1) The Benioff zone is 160 km deep, 30 km wide and 60 km long and it can be assumed to be a vertical lithospheric underthrust which is part of the Black Sea plate. (fig.1-16).

(2) The minimum average sinking rate of the lithosphere under the Carpathian arc is 1.6 cm/yr.

(3) The cold, down-going slab under the Carpathian arc is capable of generating through heat transfer a convective cell in the upper mantle which is responsible for the high heat flow in the Panonian basin.(fig.1-29).

(4) The presence of the high heat flow related to the Carpathian underthrust and the structure of the crust on either side of the Carpathian arc, which is revealed by DSS observations, supports the idea of a process of continentalisation.(fig.1-29).

(5) As a corollary of (4) it results that at the beginning of the Carpathian orogenesis these mountains were an island arc with oceanic floor on either side; the beginning of the underthrust was possible only because the slab was formed at that time of oceanic lithosphere. Through the gradual change of the crust from oceanic to continental type, the trench in front of the Carpathians disappeared and the sediments accumulated

owing to the subduction of now a continental lithosphere. As a consequence, the Carpathian underthrust could be regarded as a relic piece of oceanic lithosphere of the former Tethys Sea, a remnant of which is the Black Sea. (fig.1-32).

(6) The boundaries of the Black Sea plate to which the Carpathian underthrust belongs cannot be closed towards the west (i.e. between the Vrancea mountains and the north Anatolian fault).(fig.1-28).

3.1.2 Geological model of plates at the Carpathian arc

The first geological evidence which enabled the construction of such a model was published by this author(f.1-30,-31) in 1970 and 1971. Such a geological model of plates at the Carpathian arc is meant to give further verisimilitude to the former idealised physical model of plates in an attempt to solve such unanswered questions as the reasons for the verticality of the slab and its confinement to a 60 km horizontal front at the elbow of the mountain arc.

Our vertical geological cross-section showing the process of continentalisation since the beginning of the lithospheric underthrust to the present day is based on geological characteristics of the Carpathian region, which we discussed in chapter 1.2 (and its subdivisions, 1.2.1 and 1.2.2): the model is self-explanatory. Perhaps one should stress the fact that the important body of Neogene andesites within the East Carpathians (the Caliman-Harghita mountains) required a comparatively high energy release; on the other hand, as the andesites are acknowledged to form at depths greater than

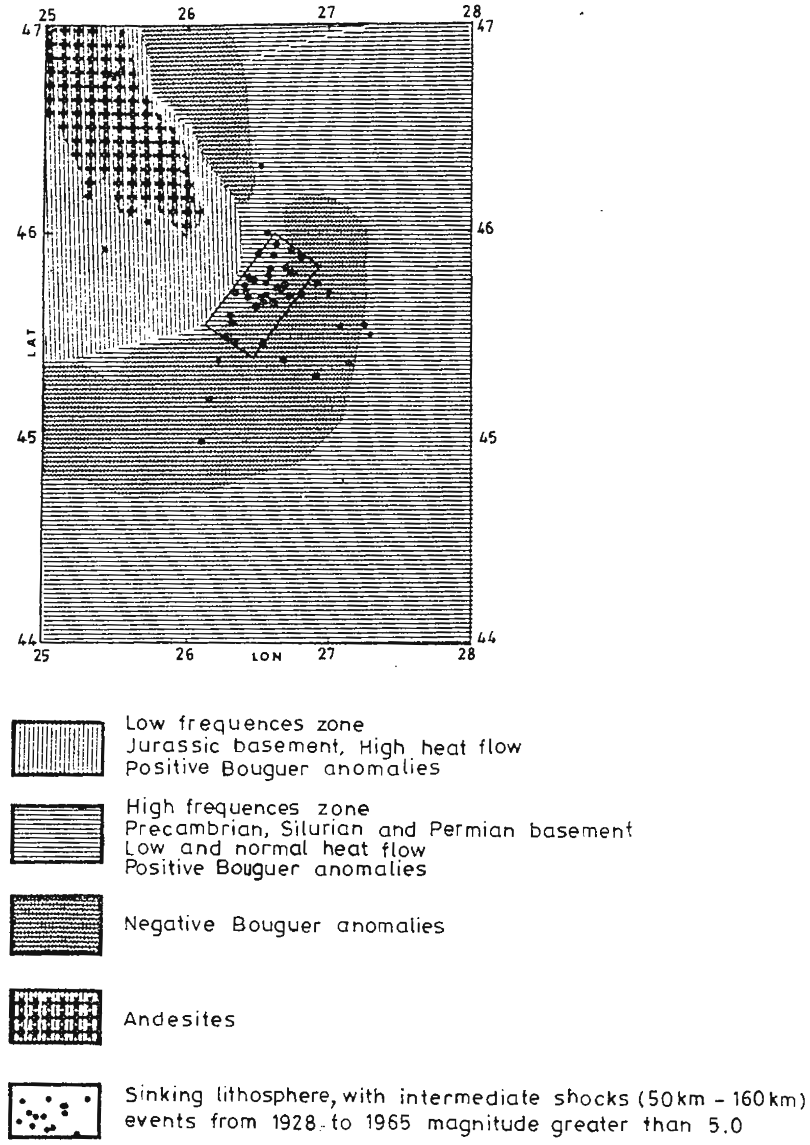


Fig. 1-30

Geophysical and geological evidence for the sinking lithosphere at the Carpathian arc (after Roman, 1970).

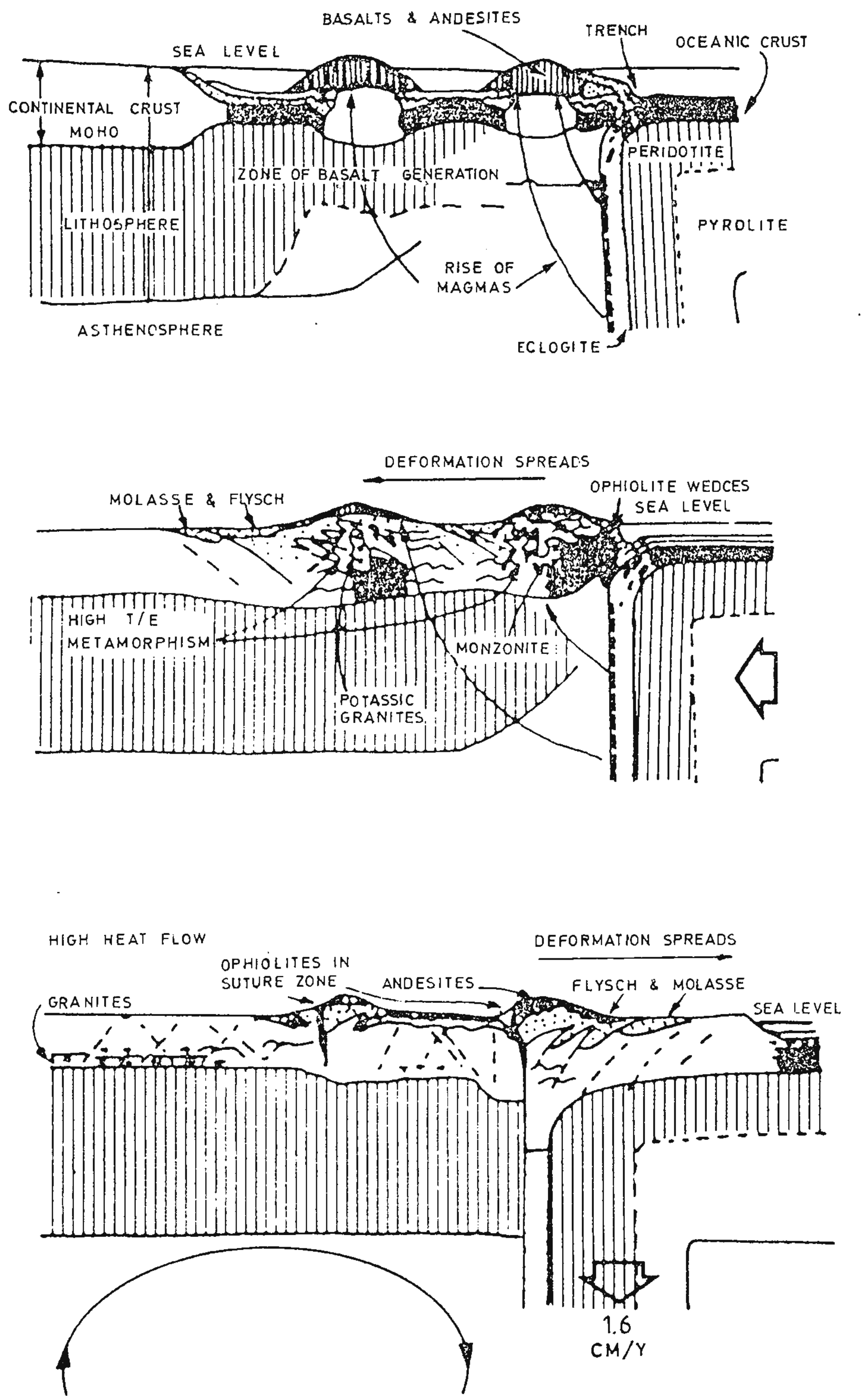


Fig.1-31

Geological model for plate evolution at the Carpathian arc of Romania (after Roman,1971). This model still does not explain how the underthrust became vertical and why it is confined to the Carpathian elbow alone (see also fig.1-35).

200 km. (Kuno, 1965), it follows that the lithospheric underthrust was much deeper during the Neogene times, and so was the seismic activity. With the progress of the continentalisation process the Carpathian trench ceased to be fed by oceanic crust and so, over the past 10 my, a good part of the slab has lost its temperature gradient through energy transfer, so that at present there remain only 160 km of the original. The age and disposition of the body of andesites are also very important in explaining the evolution of the Carpatho-Tethyan trench. It is striking that the andesitic volcanism connected with the lithospheric underthrust during the Neogene times was confined only to the range of the East Carpathian branch (from Slovakia, through S. Poland, the Ukraine and finally Moldavia) and not anywhere along the South Carpathian branch of the same Alpine belt. Furthermore, the andesites to the north of the East Carpathian range are older than the ones to the south. This suggests strongly that the Carpatho-Tethyan trench existed only along the East Carpathian mountains and that it closed first to the north, the last front of active oceanic trench being left to the south, in the region of the mountain elbow.(fig.1-35).

The implications of this process are far-reaching for the seismotectonic interpretation of the Carpathians because it gives an explanation for the confinement of the subduction zone to such a limited front: as the Carpatho-Tethyan trench closed first to the north, this must have happened more than 10 my ago, the time necessary for the disappearance of the thermal gradient through the heat transfer; consequently, the lithospheric underthrust disappeared first to the north and with it the

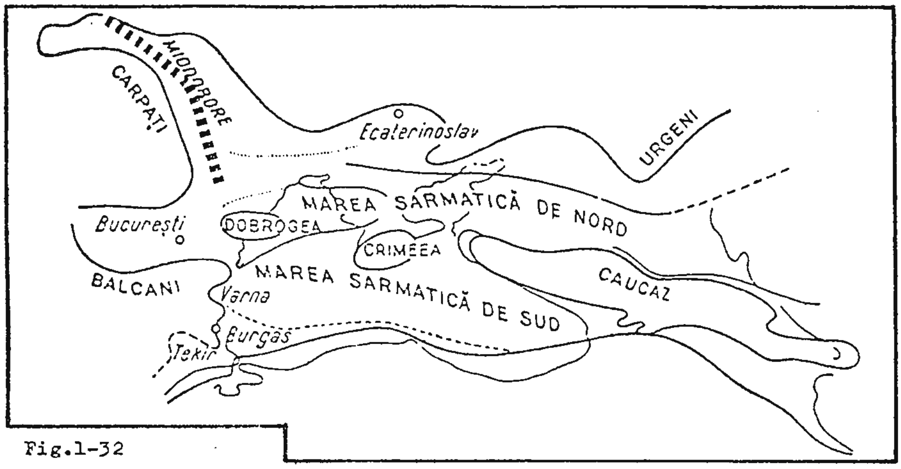


Fig.1-32

The Miocene seas of the Carpatho-Euxinic regions (after Macovei, 1958). The figure is essentially the same as fig.1-7, p.24,with the difference that the Euxinic (Black Sea) basin and the 'arm' of the sea in front of the E Carpathians is shown in more detail. This allowed us to indicate the position of the Carpathian trench during Miocene times (red dotted line) on the basis of the volcanic evidence: andesitic volcanoes were active at that time all along the E Carpathians. They first became extict to the north of the mountain range, and only lastly to the south.

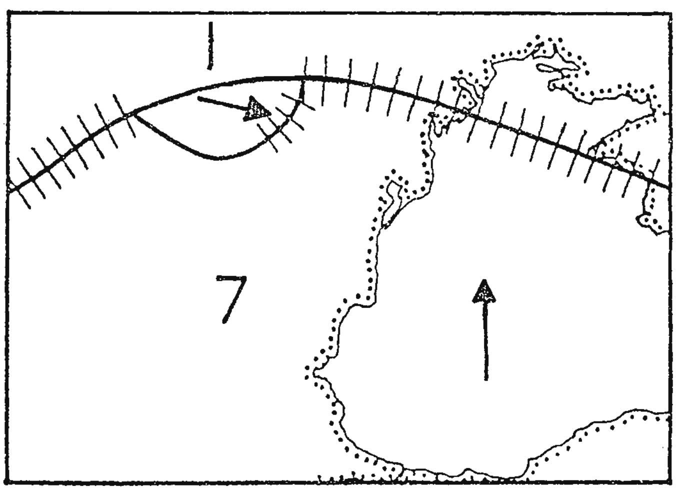


Fig.1-33

Carpathian plate model proposed by McKenzie (1972).
The consumption of the oceanic crust must occur from the side external to the Carpathian arc, and NOT from behind it, as suggested by the model: this is because of the position of the andesitic volcanoes with respect to the trench. Besides, a 'Transylvanian' (?) plate would be too small to be relevant at a global tectonic scale and would not have enough oceanic crust to produce such an extensive Benioff zone as the one under the Vrancea mountains (see also paper at the end of vol.2, Roman,1973b).

subcrustal earthquakes and the andesitic volcanism. This process gradually extended further to the south; probably less than 10 my ago there was still an active oceanic trench at the Carpathian elbow, which accounts for today's relict oceanic crust and subcrustal seismicity being confined to a mere 60 km horizontal length. Once the oceanic trench closed and the feeding process ceased, the only dynamic force to which the relict slab was subjected was the gravitational force. Due to this force the slab changed its dipping angle from the usual 45°, at a time when it used to be normally fed with new oceanic lithosphere, to an angle of 90°.

Within the framework of plate tectonics this is the only possible explanation of these major questions on the Carpathian seismicity. McKenzie (1972) wrongly interpreted my geological evidence (Roman, 1970) to suggest that the destruction of the oceanic crust occurred from behind the Carpathian arc, through the rotation of a mini-plate of the size of Transylvania (fig. 1-33). This author has explained in some detail (Roman, 1973c) why such a model, as proposed by McKenzie, cannot work; a major reason for this is the position of the andesites with respect to the subduction zone.

3.1.3 Limitation of the plate models

There are inherent limitations in our modelling technique: some of these would stem from the basis of plate tectonics itself, others would arise from our two-dimensional model. To start with the latter, any two-dimensional model would produce only a partial answer to the kinematics of an otherwise three-dimensional body, the movement of which could be described only by that of a rigid cap on a sphere. Another shortcoming is the fact that any backward extrapolation of plate evolution across continental crust is crippled by lack of information on the magnetic lineations of an oceanic floor, now completely destroyed. The presence of ophiolites is too scarce along the East Carpathians (compared to Yugoslavia and Anatolia or even the W. Alps) to support strongly an important lithospheric consumption along that front. Where it concerns the continental lithosphere, the model of plate evolution is very often in the realm of speculation.

Furthermore, we cannot possibly maintain that there is not enough seismological information to describe the movement of the Black Sea plate by means of plate tectonic interpretation: we can only observe the seismotectonic reality and concede that Plate Tectonics is still on the border between hypothesis and theory. This only gives room for more speculation which, if proved acceptable, would come in support of Plate Tectonics as a theory. In our case, the Black Sea plate is a good enough example to discuss and try to speculate upon in an attempt to solve the remaining unanswered question: is the "Black Sea plate" a plate at all and, if not, why not?

3.2 Speculation on the plate evolution in the Carpathian region

We already discussed (chapter 3.1) the great difficulty of closing up the boundary of the Black Sea plate through a line which should ideally unite to the west the Carpathian subduction zone with the westernmost end of the north Anatolian fault:

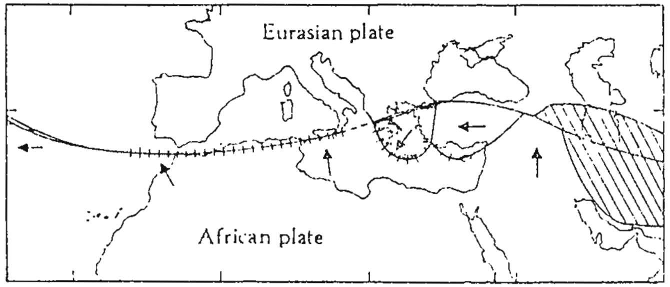
if this were possible, then we could have spoken with certainty about this entity as a real plate having all the characteristics proper to the rigid lithospheric plates. The situation being as it is, if one applies the strict principles of plate tectonics, it follows that the Black Sea region is in fact part of the Eurasian plate, as its open border to the west does not qualify it for the status of an independent plate. In support of this conclusion comes also the quasi-absence of seismic deformation along the northern boundary of the Black Sea plate, which accounts for the small motion of the whole basin (as a plate) relative to Eurasia. One could argue that the very important slip along the north Anatolian fault as well as along the Caucasus front could be interpreted as the motion of external plates (such as Turkey) relative to Eurasia.(fig.1-28).

However, if one reconsiders the facts one can easily see that the Black Sea region maintains all the characteristics of rigid plates, with just one exception: the missing link to the west. Our models also suggest that the Black Sea as a remnant of the former Tethys Sea played an independent part in the evolution of plates at the Carpathian arc. The way out of this dilemma is neither to attempt to find a border which no longer exists, nor to incorporate the Black Sea region into Eurasia, but to leave the border open and describe this entity as a "sub-plate". In other words, it would look as though at one time the Black Sea plate was a normal type of plate and that gradually its western border cratonised, creating a rigid link with Eurasia. Seismic deformations still occur along three quarters of the boundaries, but the overall movement of

Fig.1-34

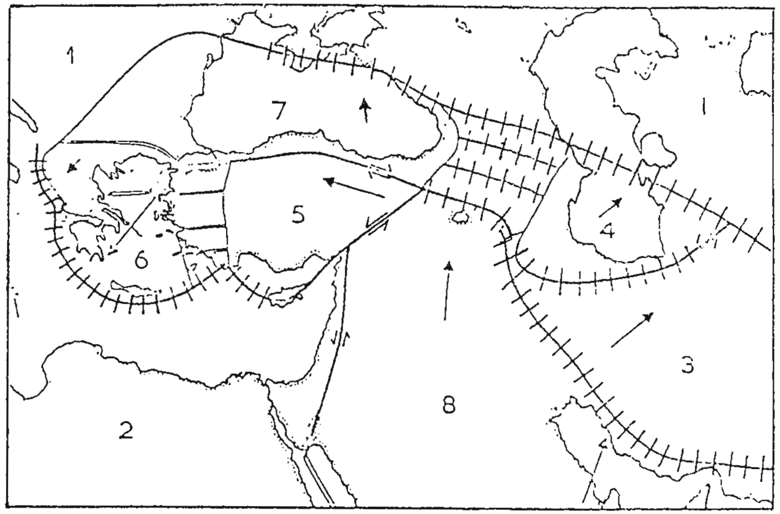
Comparative model of plates in SE Europe (after Roman,1973b).

All three authors have used the same tools of investigation (relocation of epicentres and fault plane solutions based on WWSSN seismograms) for the definition of plate boundaries across continental crust and the relative motion of plates from average slip vectors. However from figures (a) and (b) it appears that plate boundaries have changed rather substantially from 1970 to 1972, eventhough they were interpreted by the same author. Furthermore, comparing (b) to (c) shows that two different authors simultaneously find not only different boundaries for the same region, but obtain alarmingly divergent slip vectors such as for the Black Sea pointing either northward (McKenzie,1972) or northwestward (Nowroozi,1972), or the Caspian pointing northeastward in (b) and northwestward in (c). Other discrepancies appear elsewhere. The western boundary of the Black Sea should be left open as in (d) (for further discussion see also paper at the end of vol.2, Roman,1973b).



A)

Dan MeKenzie



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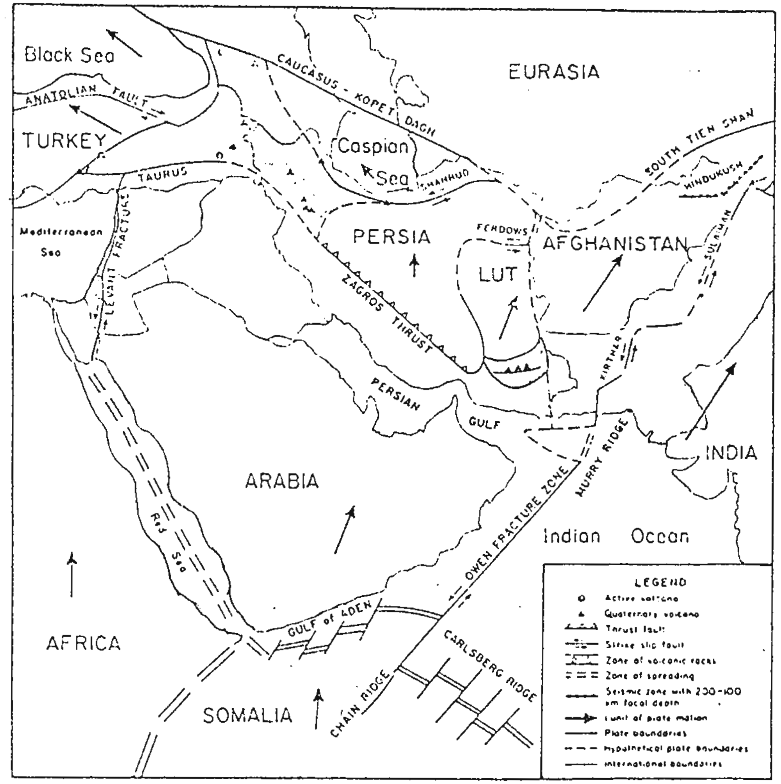
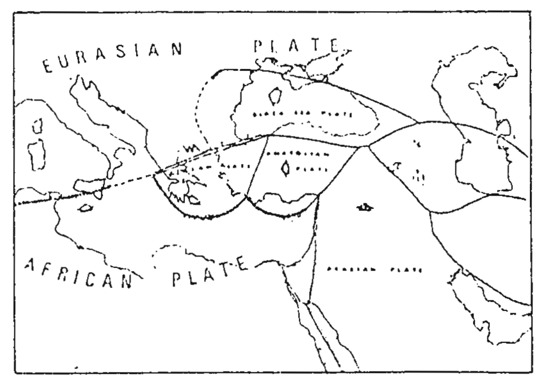


C)



D)

A) McKenzie, D. P., Nature, 226, 239(1970).

B) McKenzie, D. P., Geophys. J. Roy. astr. Soc., 30, 109(1972).

C) Nowroozi, N. N., Bull. Seism. Soc. Am., 62, 823(1972).

D) Roman, C., Mem. 12th Europ. Seismol. Congr, 101, 37(1971).

Fig. 1-34

the sub-plate is reduced to a minimum.

A sub-plate should then be a conventionally rigid plate which was once active, which is formed by a tectonic entity of continental and oceanic crust and is delimited partly by discontinuities which are no longer active, or have little seismic activity, and also partly by seismically active faults.

Would there be any other sub-plates? The Adriatic plate would probably qualify for such a definition as its southern border does not appear to be well defined to make possible the link between the Sicilian trench and Albania. The confusion over this missing link allowed for this sub-plate sometimes to be considered to belong either to the African or to the Eurasian plates and at other times to be thought even a plate on its own (fig.1-34).

Speculating further on the future of the Black Sea sub-plate, one could assert with some certainty that in a few million years' time the subcrustal earthquakes under the Carpathian arc would disappear, due to the heat transfer, and that the northern front of shallow seismicity from the Carpathians through the Crimea to the Caucasus would completely disappear because of further cratonisation. At that stage the sub-plate would be incorporated into the Eurasian plate. So one could consider the status of a sub-plate as an intermediate stage between an independent small rigid plate and its subsequent inclusion into a larger rigid plate. The process could probably be performed in reverse, when new trenches and faults are created within large rigid plates, but the breakage is not complete enough to allow for the creation of an independent plate; such examples exist in the western Pacific.

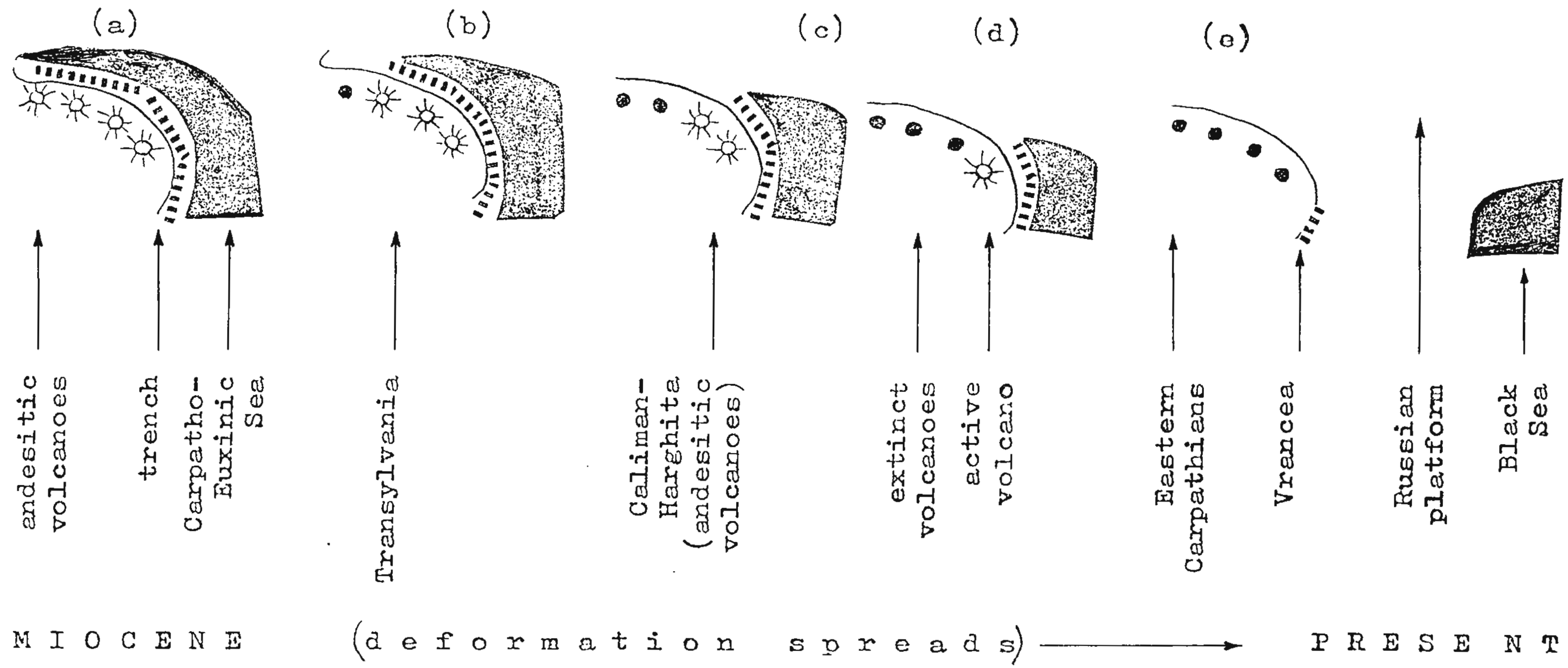


Fig.1-35

Model for the evolution of the E Carpathian trench. Though speculative, this model is based on geological evidence, and is meant to explain why the Benioff zone is vertical and confined to a 60 km horizontal front (see text).

D. conclusions

CHAPTER 4

Conclusions on the Carpathian Seismotectonics

4.1 On the seismicity

The Benioff zone is confined to a vertical parallelepiped tangent to the Carpathian arc, oriented N 35°E, with a horizontal length of 60 km, width of 30 km and depth of 160 km. Between the 30 km and 60 km depths there is a zone of minimum seismic activity, whilst between 100 km and 160 km there is a zone of maximum seismic activity. Beyond the 160 km depth there is probably a low velocity layer.

4.2 On the cause of seismicity

The nest of subcrustal foci under the Carpathian arc is caused by a relic piece of lithosphere, which once was part of the former Tethian oceanic floor now sinking, under the gravitational force at a minimum average rate of 1.6 cm/yr.

4.3 On the related physical phenomena

The energy transfer caused by the cold down-going slab seems to be responsible for the formation of a convective cell in the upper mantle capable of producing a high heat flow in Hungary. The presence of the high heat flow in the intra-Carpathian basin (Vienna, Panonian and Transylvanian basins) is the cause of the late arrivals (positive travel-time residuals) at the seismic stations in that region; early arrivals (negative P travel-time residuals) correspond to a zone of low heat flow in the Black Sea. The zone of lithospheric underthrust at the Carpathian arc also corresponds to an area of subsidence of 1 mm/yr in contrast to the 2-3 mm/yr uplift of the Southern Carpathians. The gravity low is due to the thick packet of sediments (18 km at the arc) and the "cuvette" type of feature of the Moho in the zone of subsidence.

4.4 On the related geological phenomena

The Carpathians were an island arc in the Tethys Sea at the time of the Alpine orogeny. The oceanic crust of what is now the intra-Carpathian basin underwent a rapid continentalisation process speeded up by the high heat flow which granitised the bottom of the sedimentary layer; on a lesser scale the process of continentalisation occurred on the other side of the arc, in the Carpathian foreland and the Black Sea basin, where the crust is partly oceanic and partly of an intermediate type (e.g. between purely oceanic and purely continental). The morphology of the flysch and of the Eastern Carpathian eugeosyncline suggests that the trench, under which the Tethian oceanic floor was destroyed, stretched all along the Eastern Carpathians from Slovakia, through Southern Poland, the Ukraine and Moldavia.

4.5 On the plate tectonic interpretation

The Carpathian lithospheric underthrust is part of a trench which was consuming oceanic crust coming from the east and southeast, from the region of a Black Sea plate.

The age of the Neogene andesitic volcanism along the Eastern Carpathians suggests that the Carpatho-Tethian trench closed first to the north, in the regions of Slovakia, Poland and the Ukraine, and only much later in Moldavia. This slow closure of the trench from north to south is connected with the anticlockwise movement of Italy and the closure of the Adriatic Sea, and it accounts for the gradual disappearance through heat transfer of the down-going slab along the Eastern Carpathians. With the trench ceasing to be fed through crushing of the Eastern Carpathians against the Russian platform the remainder of the sinking lithosphere changed its angle from what was probably a 45° dip to what is now 90°, due to the action of the gravitational force, which also accounts for the accumulation of the thick packet of sediments in the Vrancea foreland. Due to a partial cratonisation process, the Black Sea plate's western boundary ceased to be seismically active. This puts the Black Sea in the special category of sub-plates.

This is only a brief outline of what are considered to be the main conclusions. Detailed conclusions are at the end of each of the subdivisions of chapters 2 and 3.

E. addendum

ADDENDUM 1

On the P travel-time residuals of the Carpathian events.
(see also chapter 2.2, Part 1, page 73 and paper Roman,1973c in the selection of publications at the end of Part 2)

The purpose of including this addendum is NOT to unnecessarily burden the content of the dissertation. Its aim is threefold: firstly to illustrate that the relocation of earthquakes is not as simple as it may appear; this also shows, incidentally, the versatility of Bolt's program. Secondly, it is meant to serve as a reference for the possible future developments in the study of P travel-time residuals of the Carpathian earthquakes. Thirdly, and most important, the following sequence of residual spheres supports the argument contained in chapter 2.2 on the study of the P travel-time residuals in the Carpathians.

The essence of this argument is that none of the residual spheres of earthquakes at the Carpathian arc, whether shallow or at intermediate depths, show any sign of the negative P travel-time residuals in the azimuth of the sinking lithosphere, as posrulated by Davies & McKenzie (1969). Had these authors been correct, then we would have found such an anomaly in a N30°E azimuth, which is the azimuth of the vertical underthrust at the Carpathian arc. This is discussed in some detail in chapter 2.2 and it is not necessary to repeat what is stated both there and in our publication (Roman, 1973c) found in the 'pocket' at the end of the second volume of this dissertation.

The layout of the addendum 1 is as follows: a list of shallow events numbered 1-17, followed by their respective residual spheres (numbers in the table correspond to those in the figures); a list of subcrustal events for the same period, 1928-1965, numbered 1-53, also followed by their respective residual spheres. The program and the symbols used are the same as the ones described by Bolt (1960) and presented by Davies & McKenzie (1969). Plus signs represent positive residuals (late arrivals) and open circles negative residuals (early arrivals). The residuals range from -2.5 seconds to +2.5 seconds, depending on the size of the symbols. Larger residuals are removed and consequently do not influence the relocation.

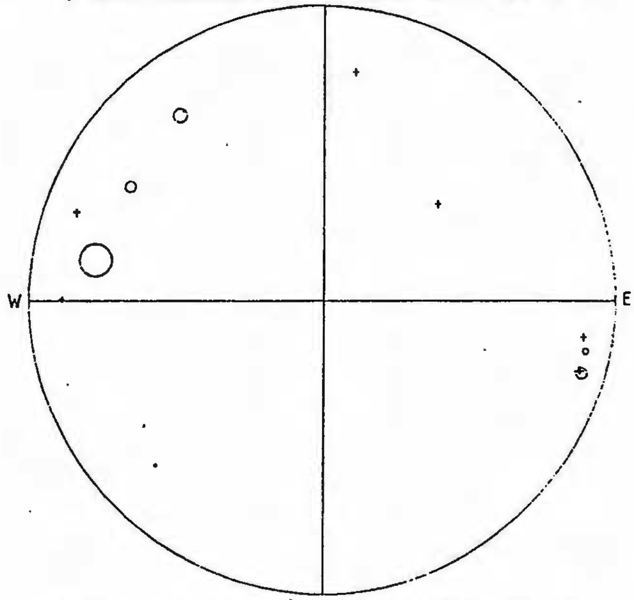
List of shallow events (h $\leq$ 50 km) at the Carpathian arc, 1928-1965, relocated through Bolt's program

(the entries are from the BCIS and ISC bulletins)

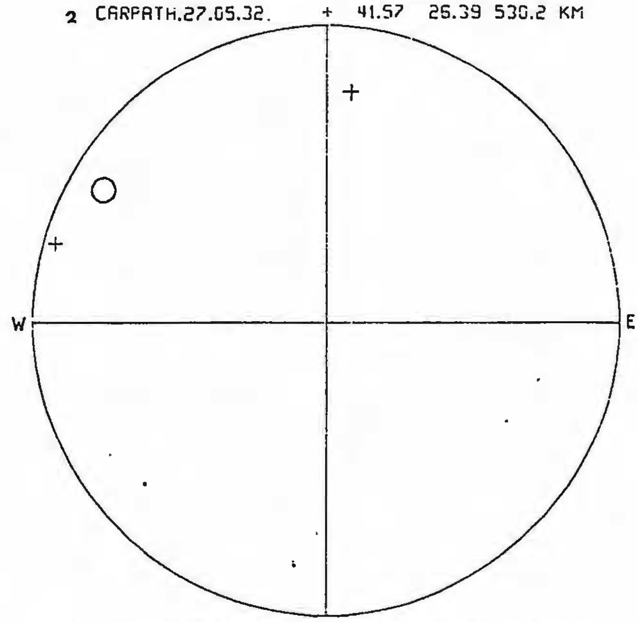
No.	Event	LAT. N °	LON. E °	NSTA	DEPTH km	SELAT km	SELON km	SEDEPTH km	SETIME sec
1	20.05-1929	46.26	26.52	14	30	11.8	3.8	52.5	5.6
2	27.05.1932	41.57	26.39	17	-	60.6	13.2	35.0	3.9
3	02.02.1934	46.44	26.23	19	0	32.3	9.7	0.0	1.3
4	01.11.1936	45.88	26.73	15	0	16.3	4.9	0.0	1.0
5	28.04.1943	45.83	26.96	12	0	16.5	14.5	0.0	1.6
6	12.03.1945	45.82	26.14	27	0	10.3	8.7	0.0	1.1
7	20.07.1955	45.01	27.82	5	0	-	-	0.0	-
8	04.01.1956	45.76	26.32	6	0	4.1	5.7	0.0	0.5
9	08.03.1956	45.58	26.81	4	0	10.9	1.0	0.0	1.3
10	11.03.1956	45.53	26.65	5	0	4.0	5.2	0.0	0.4
11	18.04.1956	46.09	27.86	14	0	7.7	7.8	0.0	0.8
12	04.11.1956	46.12	27.50	5	0	11.1	24.8	0.0	2.2
13	30.04.1957	46.37	27.76	4	0	66.7	74.8	0.0	7.5
14	07.04.1958	45.82	26.37	5	8	2.1	4.1	8.0	0.8
15	31.05.1959	45.85	27.33	106	37	4.5	3.0	5.6	0.5
16	04.01.1960	45.04	26.70	95	33	4.1	2.4	11.5	1.4
17	16.09.1965	46.07	27.01	12	38	7.0	5.6	15.1	0.7

NSTA = number of seismic observations
SELAT = standard error for relocated latitude of event
SELON = standard error for relocated longitude of event
SEDEPTH = standard error for relocated depth of event
SETIME = standard error for the origin-time of event

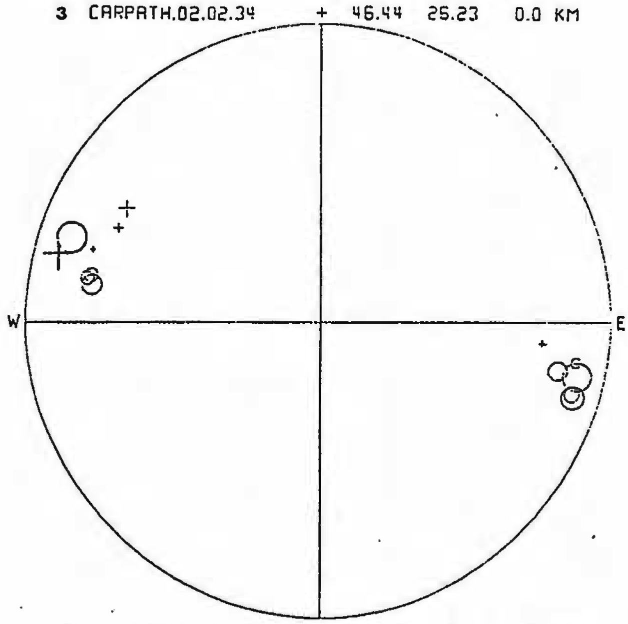
1 CARPATH.20.05.29 + 46.26 26.52 29.6 KM



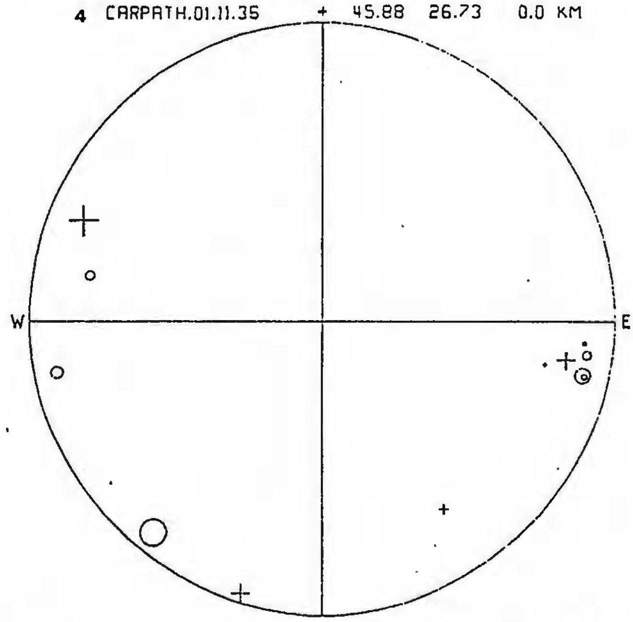
2 CARPATH.27.05.32. + 41.57 26.39 530.2 KM



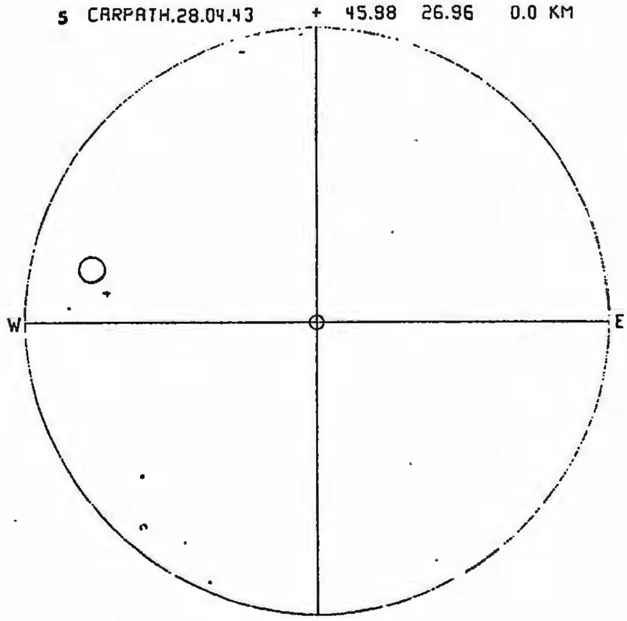
3 CARPATH.02.02.34 + 46.44 25.23 0.0 KM



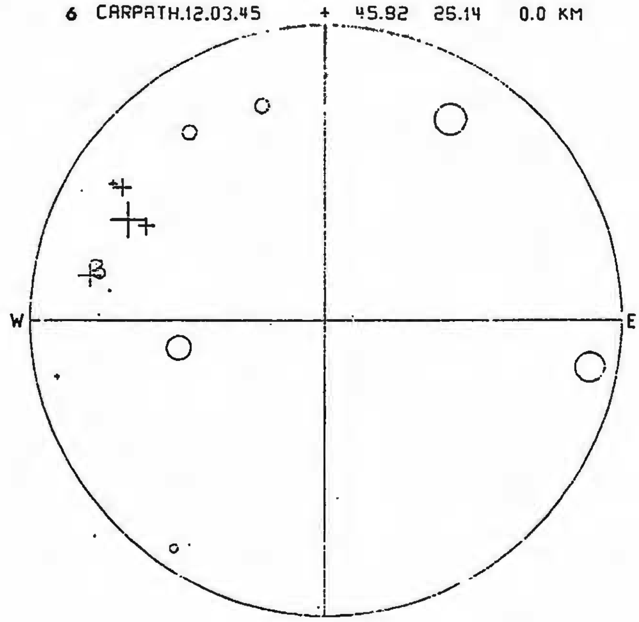
4 CARPATH.01.11.35 + 45.88 26.73 0.0 KM



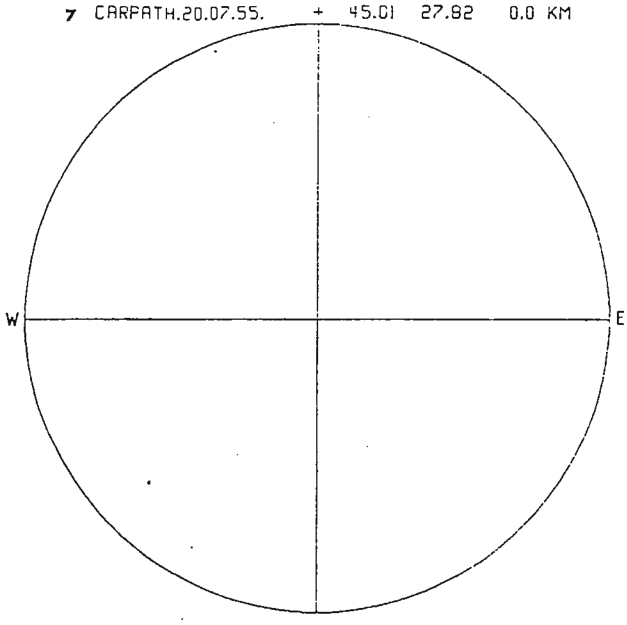
5 CARPATH.28.04.43 + 45.98 26.96 0.0 KM



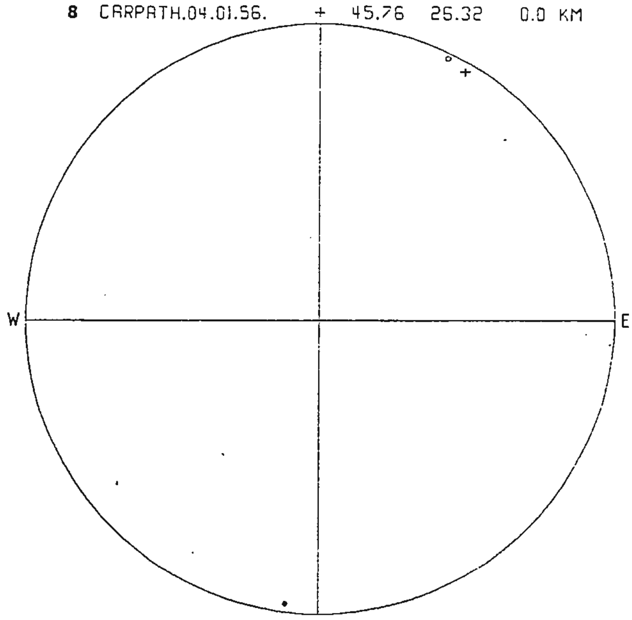
6 CARPATH.12.03.45 + 45.92 26.14 0.0 KM



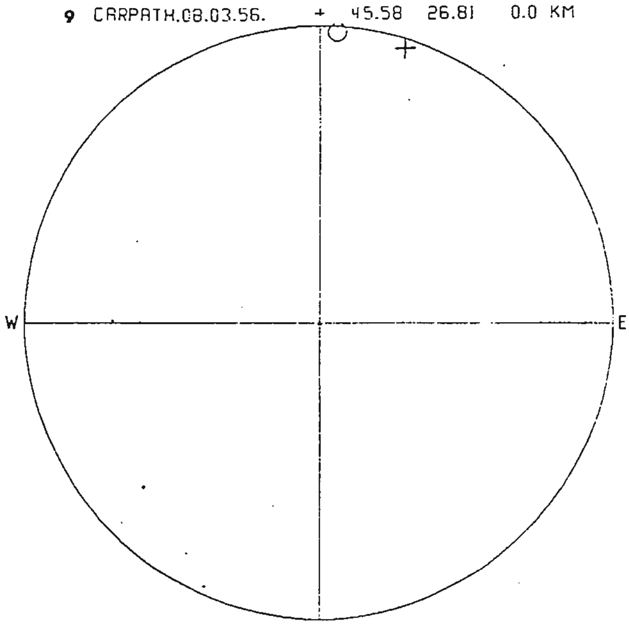
7 CARPATH.20.07.55. + 45.01 27.82 0.0 KM



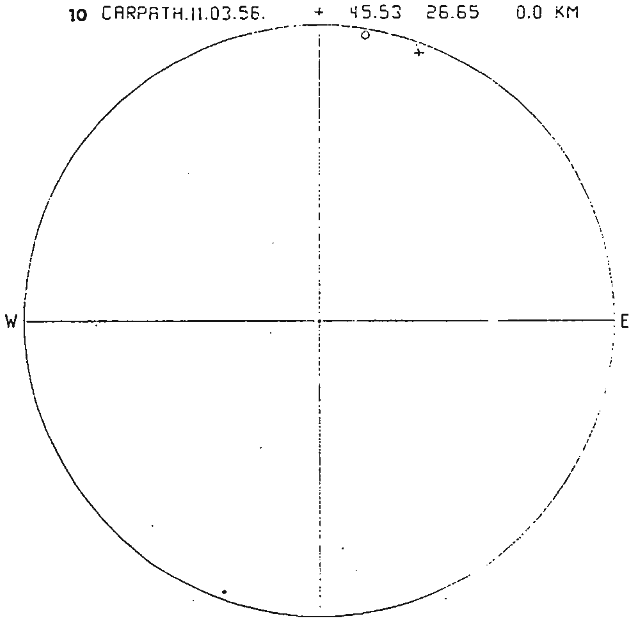
8 CARPATH.04.01.56. + 45.76 25.32 0.0 KM



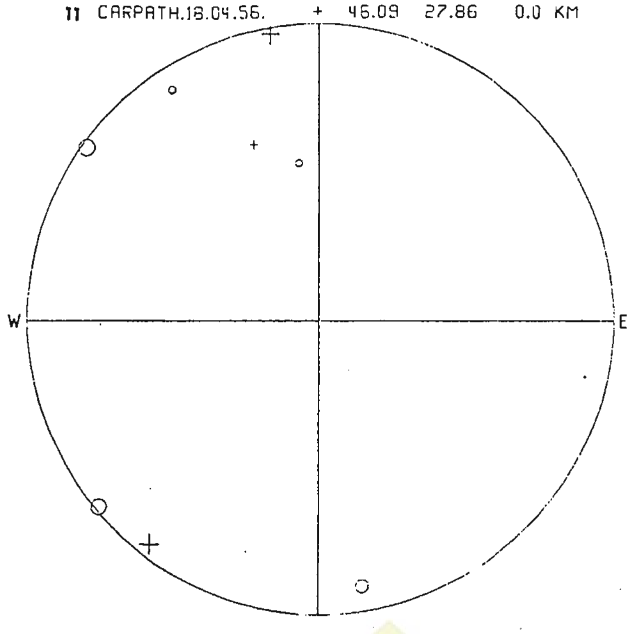
9 CARPATH.08.03.56. + 45.58 26.81 0.0 KM



10 CARPATH.11.03.56. + 45.53 26.65 0.0 KM



11 CARPATH.18.04.56. + 46.09 27.86 0.0 KM



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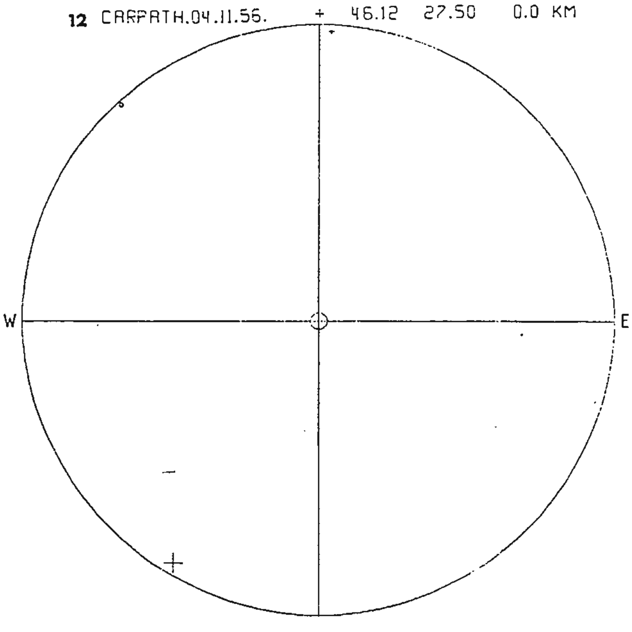
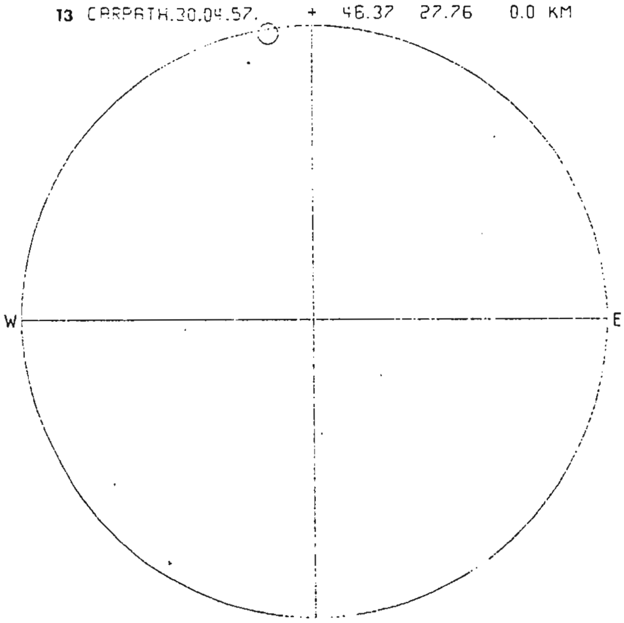
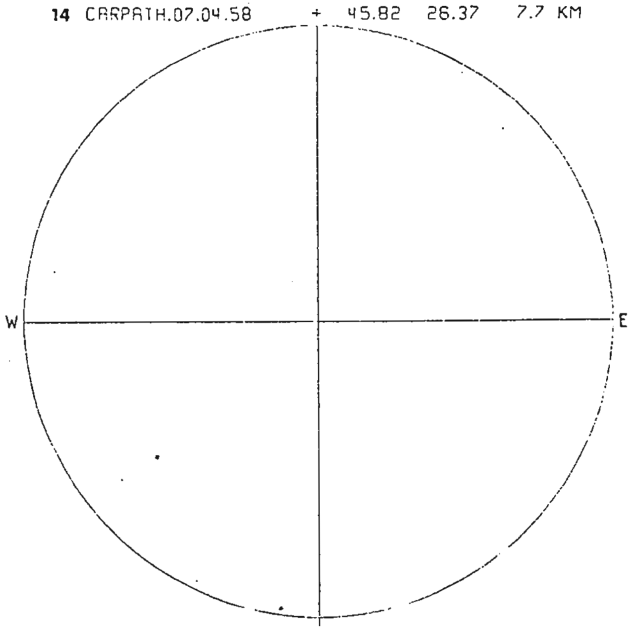


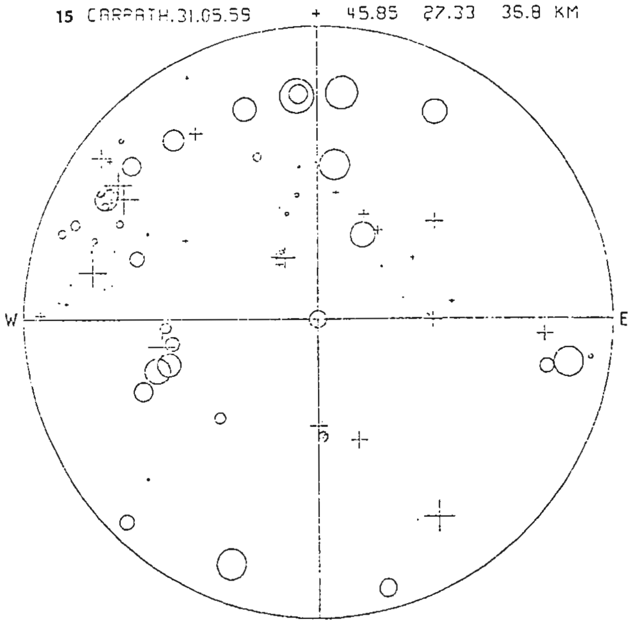
13 CARPATH.30.04.57. + 46.37 27.76 0.0 KM



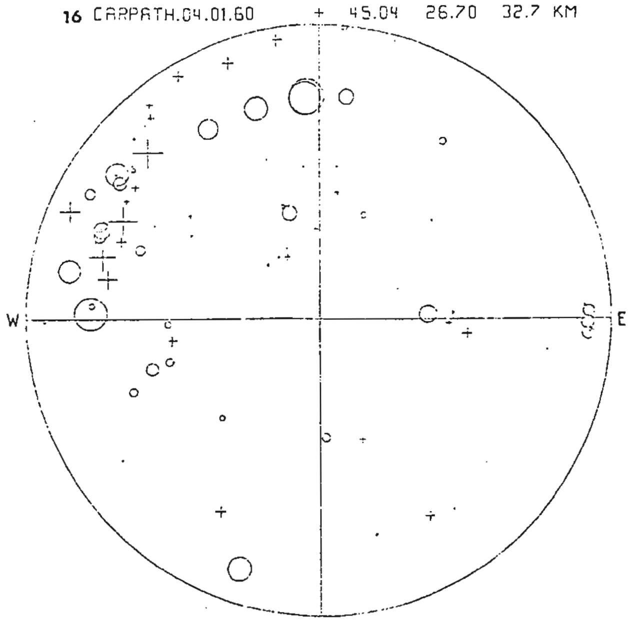
14 CARPATH.07.04.58 + 45.82 26.37 7.7 KM



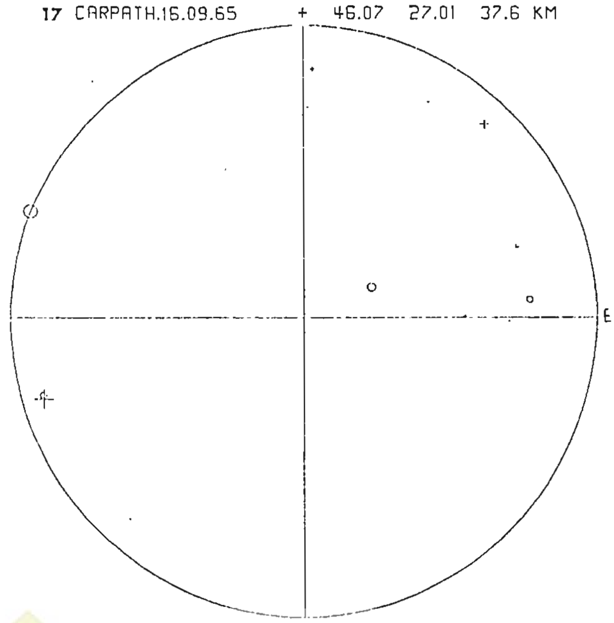
15 CARPATH.31.05.59 + 45.85 27.33 35.8 KM



16 CARPATH.04.01.60 + 45.04 26.70 32.7 KM



17 CARPATH.16.09.65 + 46.07 27.01 37.6 KM



Table

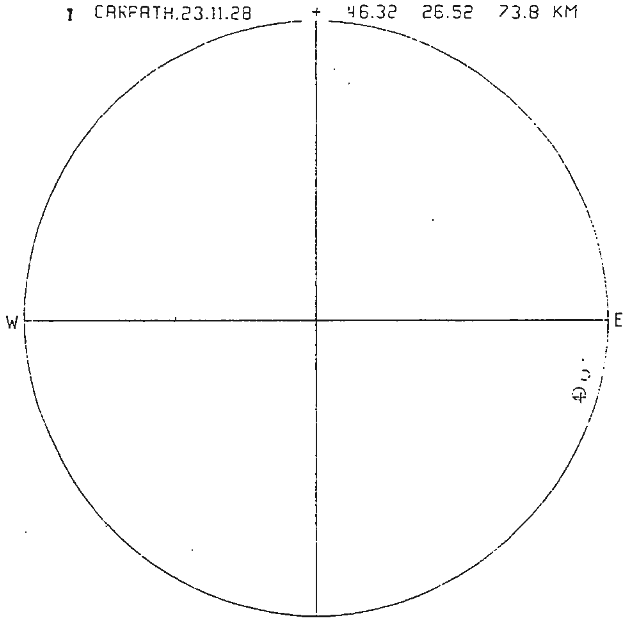
Subcrustal events at the Carpathian arc, 1928-1965 (h > 50 km), entries from the BCIS and ISC bulletins

No.	Event	Lat °N	Lon °E	N	Depth km	Selat km	Selon km	Sedepth km	Setime sec
1	23.11.28	46.32	26.52	8	74	15.0	4.6	26.0	0.9
2	01.11.29	45.78	26.44	67	44	6.4	2.9	11.5	0.6
3	29.03.34	45.77	26.47	74	86	5.8	2.1	8.8	0.6
4	13.07.35	45.95	26.62	46	87	9.8	4.0	21.3	0.9
5	17.05.36	45.19	26.15	20	160	24.1	9.5	41.7	1.3
6	13.07.38	45.89	26.60	33	102	7.8	3.2	13.7	0.5
7	05.09.39	45.83	26.69	29	120	9.3	5.0	12.2	0.7
8	24.06.40	45.92	26.74	40	114	5.8	4.1	10.1	0.6
9	22.10.40	45.69	26.42	85	122	4.9	2.2	5.1	0.4
10	10.11.40	45.74	26.63	148	111	6.1	2.7	6.0	0.6
11	08.11.40	45.57	26.31	17	141	10.4	9.2	16.9	1.1
12	11.11.40	46.00	26.55	34	114	11.1	6.6	19.9	1.0
13	19.11.40	45.55	27.25	15	178	19.7	7.5	31.3	1.2
14	23.11.40	45.46	26.53	9	138	21.6	8.9	37.9	1.2
15	13.04.42	44.98	26.10	7	187	45.7	70.4	94.4	9.2
16	07.09.45	45.90	26.49	52	64	5.4	2.6	7.6	0.6
17	09.12.45	45.73	26.66	50	72	7.3	3.5	9.2	0.7
18	03.10.46	45.47	26.33	25	117	13.2	5.1	20.3	0.9
19	03.11.46	45.60	26.30	42	131	7.4	4.2	10.7	0.6
20	17.10.47	45.83	26.58	21	122	9.0	3.3	13.3	0.6
21	13.03.48	45.66	26.59	14	163	16.6	5.7	13.8	0.7
22	29.04.48	45.66	26.51	10	158	11.0	3.2	11.8	0.4
23	29.05.48	45.79	26.57	66	129	6.0	2.7	7.3	0.5
24	26.12.49	45.70	26.55	21	133	11.6	5.1	10.7	0.6
25	16.01.50	45.47	26.32	33	113	8.8	3.3	8.5	0.6
26	20.06.50	45.75	26.40	48	141	6.2	3.2	8.4	0.5
27	14.07.50	45.71	26.99	15	53	7.1	7.3	11.5	0.7

Table contd.

No.	Event	Lat °N	Lon °E	N	Depth km	Selat km	Selon km	Sedepth km	Setime sec
28	18.03.51	45.75	26.68	16	146	4.9	3.3	6.2	0.4
29	16.01.52	45.37	27.14	15	73	9.1	11.4	19.5	1.2
30	03.06.52	45.55	27.08	45	54	11.0	6.5	20.2	0.9
31	03.03.52	45.50	26.28	46	148	3.7	2.0	4.2	0.3
32	01.05.55	45.65	26.49	30	125	5.0	4.2	10.1	0.8
33	24.12.55	45.70	26.80	6	100	398.8	785.2	0.0	67.6
34	27.12.55	45.70	26.80	6	100	398.8	785.2	0.0	67.6
35	16.02.56	45.92	25.42	8	109	12.8	20.5	26.3	1.0
36	07.05.56	45.76	26.92	12	146	5.7	8.7	6.7	0.5
37	23.09.56	45.70	26.80	4	100	5.7	8.8	6.7	0.5
38	18.11.56	45.69	26.70	12	160	7.1	5.8	6.9	0.6
39	02.09.57	45.51	27.29	8	125	12.7	27.0	17.0	1.5
40	02.12.57	46.05	25.72	8	96	7.5	10.8	13.2	0.8
41	23.12.57	45.38	26.67	21	59	5.7	5.2	8.5	0.5
42	27.03.58	45.88	26.80	12	106	7.1	6.9	10.1	0.6
43	09.06.58	45.38	26.22	10	138	31.5	17.8	20.8	2.2
44	25.06.58	45.67	26.53	20	146	5.3	4.4	6.6	0.4
45	26.06.59	45.69	26.52	41	136	4.9	3.7	6.1	0.4
46	30.06.59	45.65	26.48	25	119	5.1	3.5	8.0	0.5
47	19.08.59	45.79	26.41	41	157	5.1	3.4	6.3	0.4
48	26.01.60	45.74	26.39	102	152	3.2	1.8	3.7	0.3
49	13.10.60	45.71	26.33	105	152	3.2	1.8	3.7	0.3
50	14.01.63	45.81	26.73	110	111	3.4	1.6	3.8	0.2
51	17.06.64	45.72	26.40	15	192	13.7	10.7	13.1	0.8
52	08.08.64	45.31	26.90	11	67	9.3	15.0	17.6	1.0
53	10.01.65	45.76	26.55	138	134	2.8	1.5	2.7	0.2

1 CARPATH.23.11.28 + 46.32 26.52 73.8 KM



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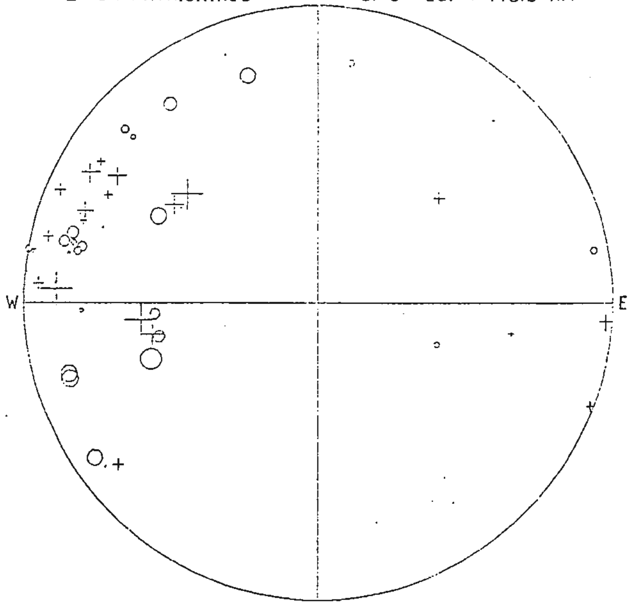
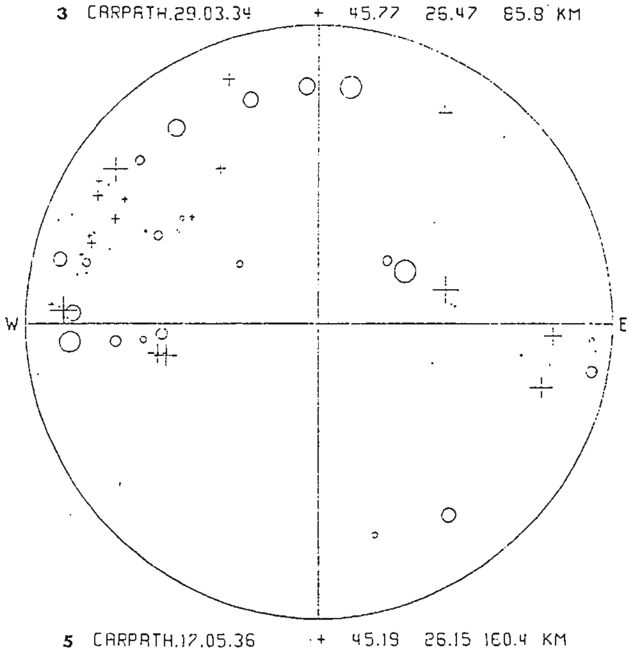
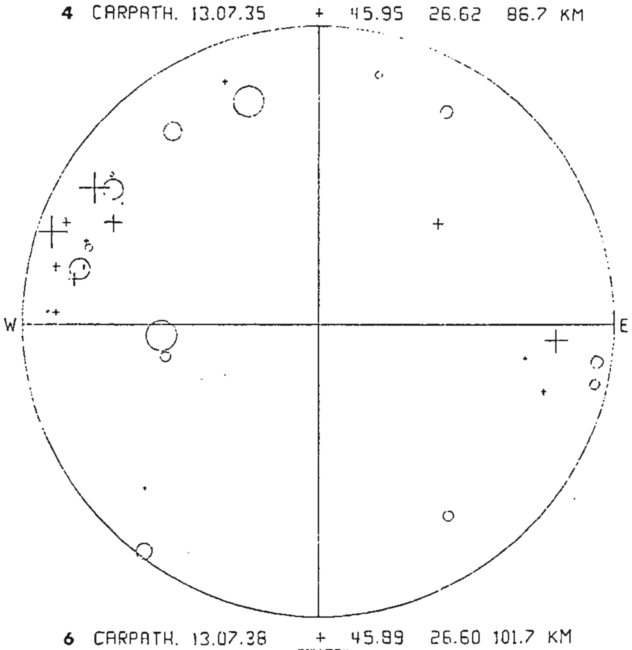


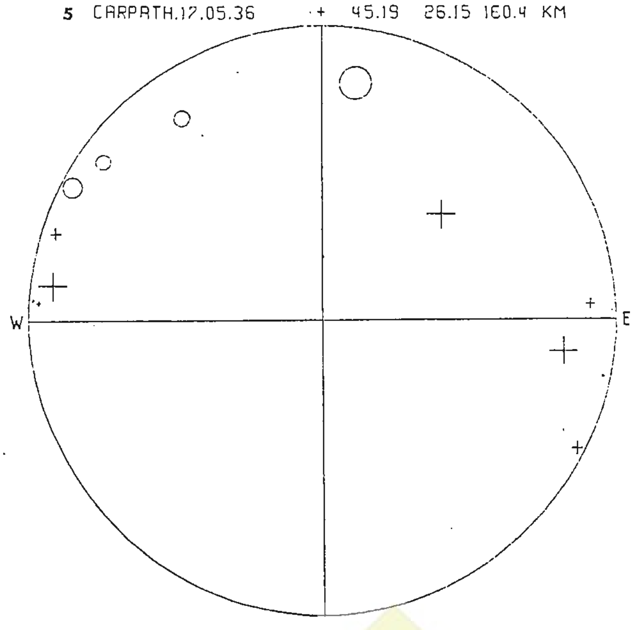
3 CARPATH.29.03.34 + 45.77 26.47 85.8 KM



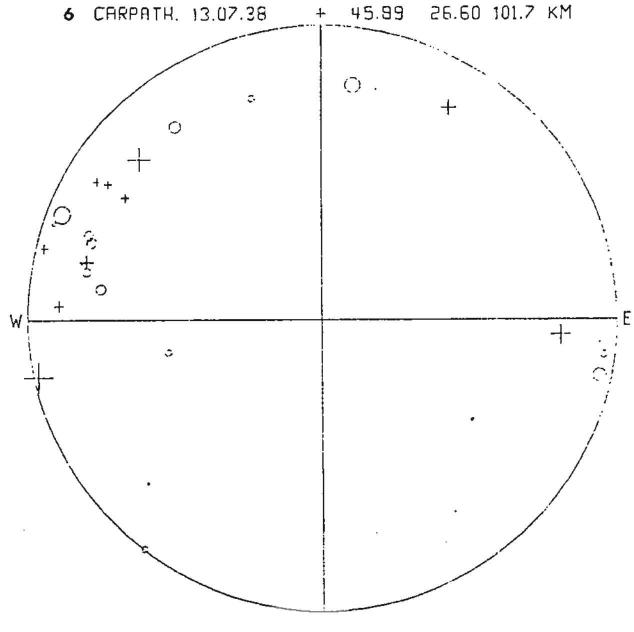
4 CARPATH. 13.07.35 + 45.95 26.62 86.7 KM



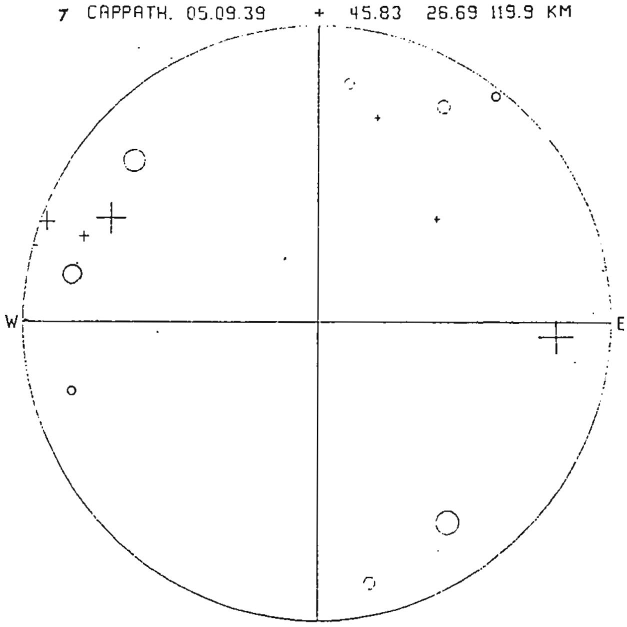
5 CARPATH.17.05.36 + 45.19 26.15 160.4 KM



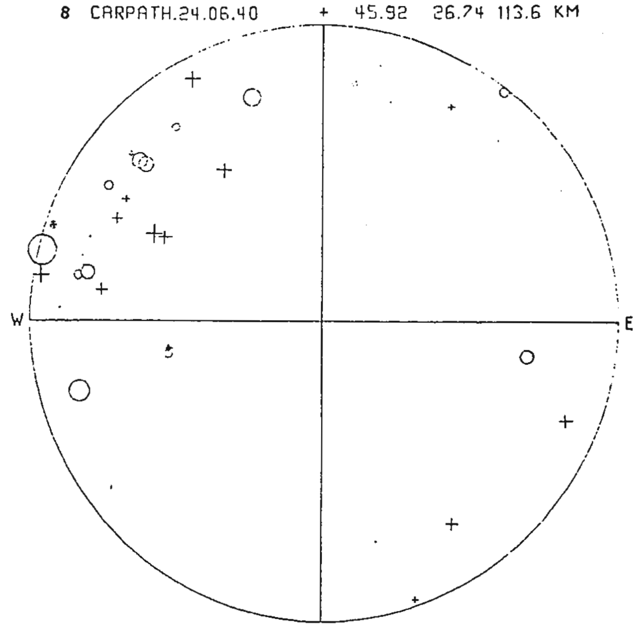
6 CARPATH. 13.07.38 + 45.89 26.60 101.7 KM



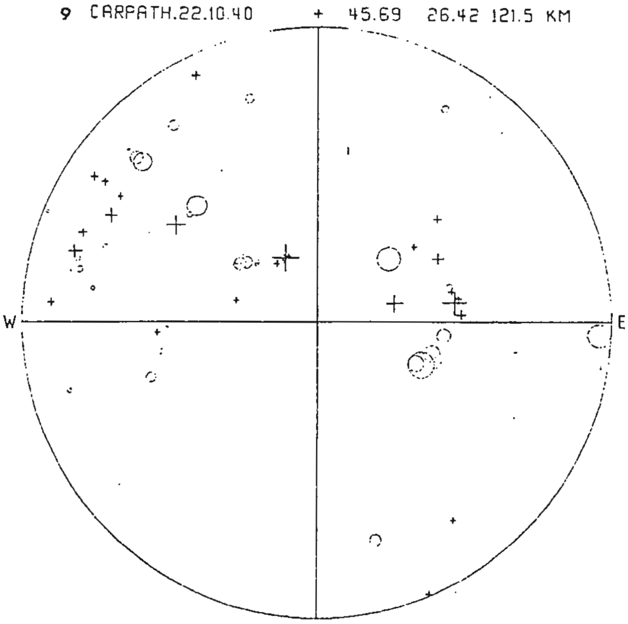
7 CARPATH. 05.09.39 + 45.83 26.69 119.9 KM



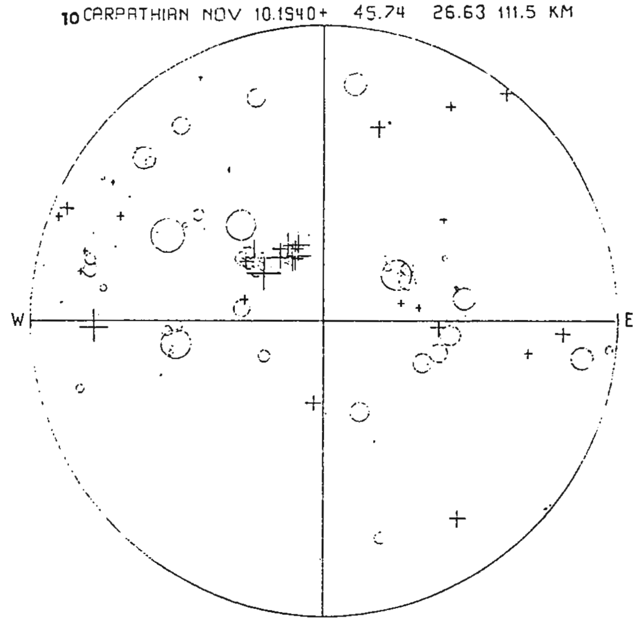
8 CARPATH.24.06.40 + 45.92 26.74 113.6 KM



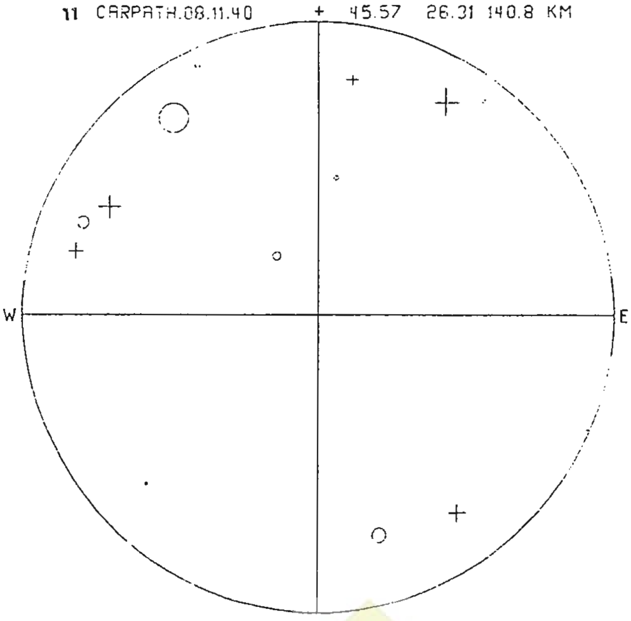
9 CARPATH.22.10.40 + 45.69 26.42 121.5 KM



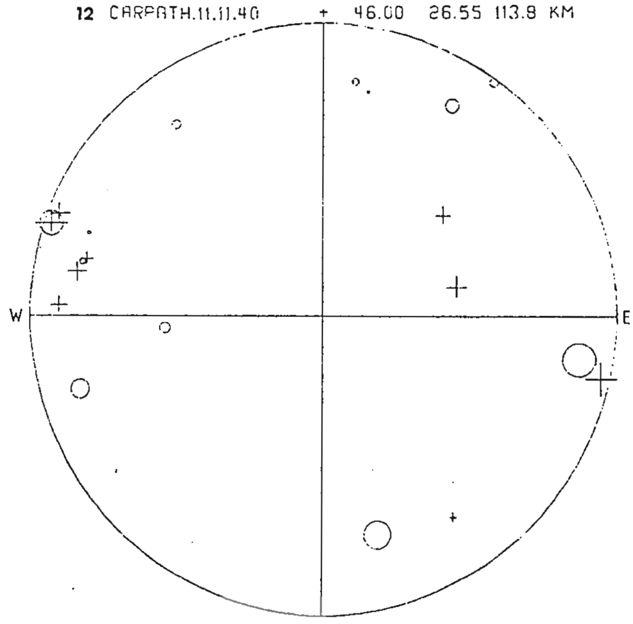
10 CARPATHIAN NOV 10.1940 + 45.74 26.63 111.5 KM



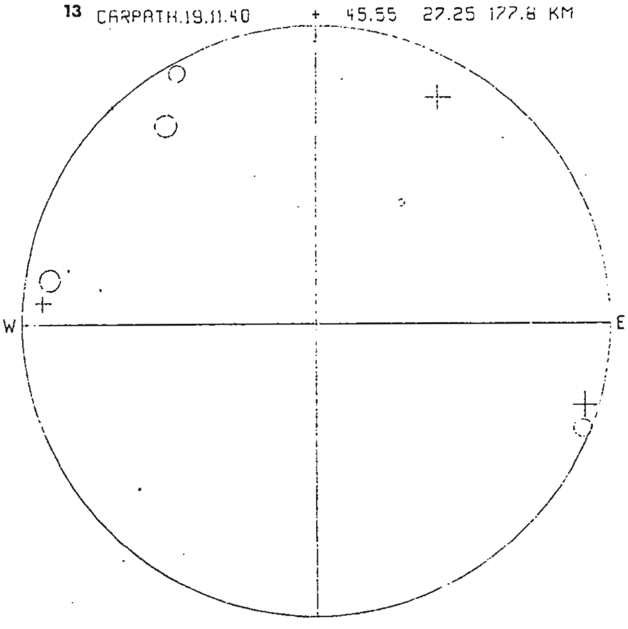
11 CARPATH.08.11.40 + 45.57 26.31 140.8 KM



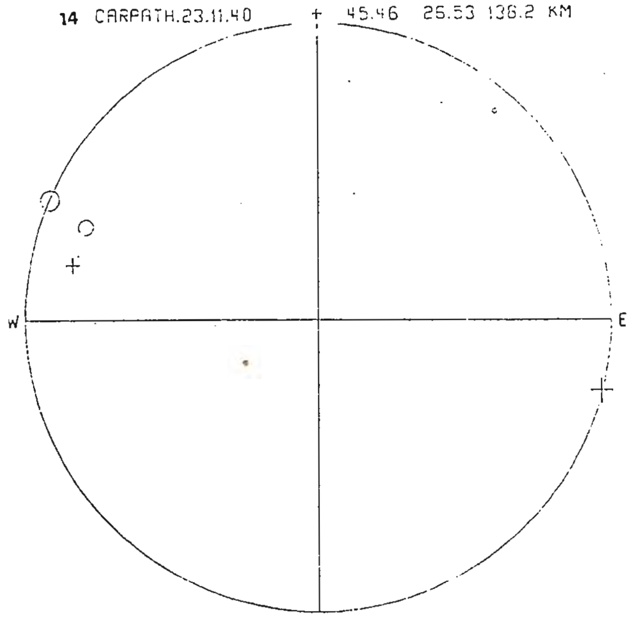
12 CARPATH.11.11.40 + 46.00 26.55 113.8 KM



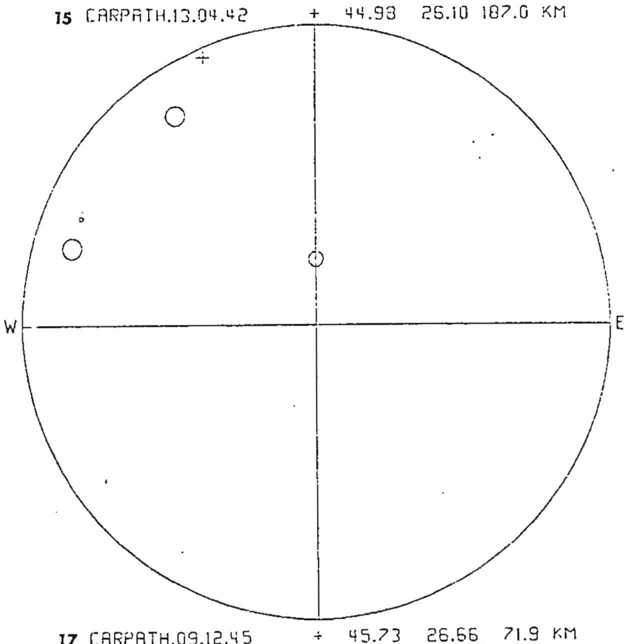
13 CARPATH.19.11.40 + 45.55 27.25 177.8 KM



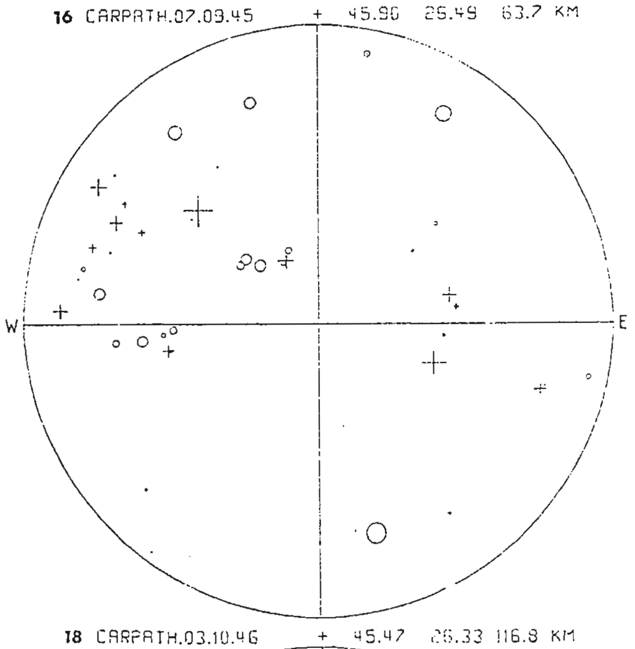
14 CARPATH.23.11.40 + 45.46 26.53 136.2 KM



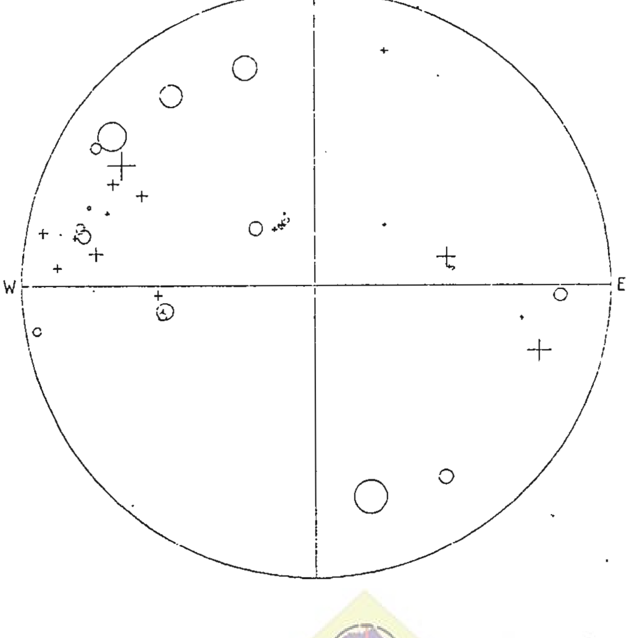
15 CARPATH.13.04.42 + 44.93 26.10 187.0 KM



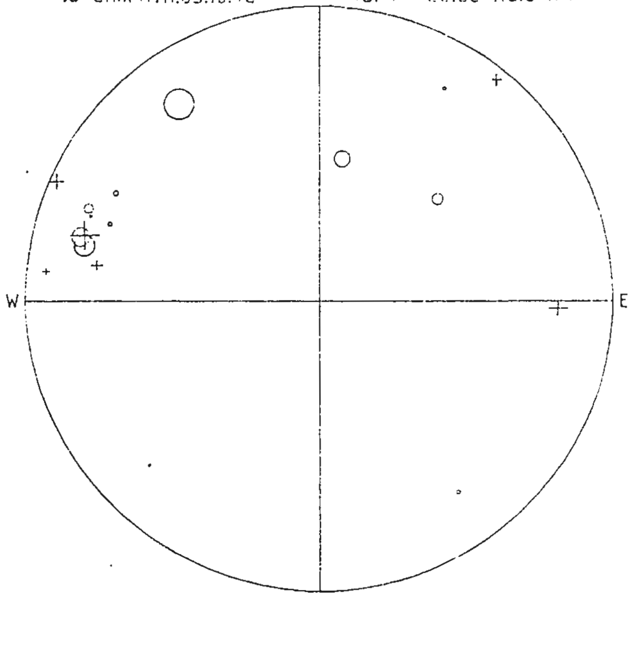
16 CARPATH.07.09.45 + 45.90 26.49 63.7 KM



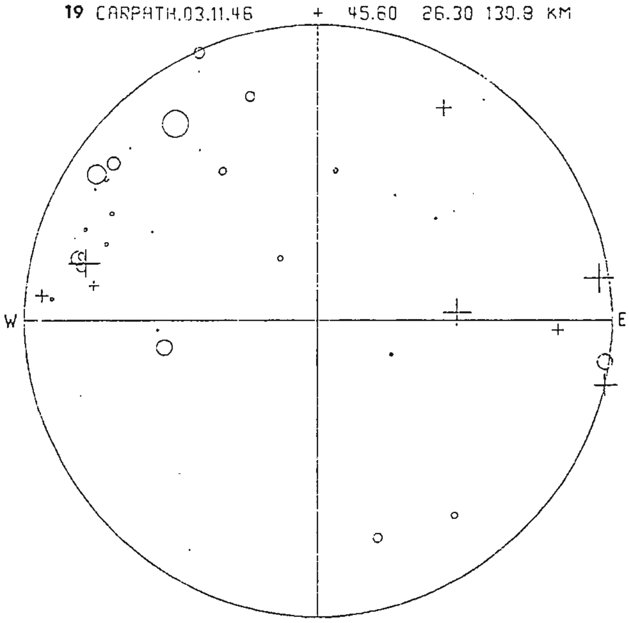
17 CARPATH.09.12.45 + 45.73 26.66, 71.9 KM



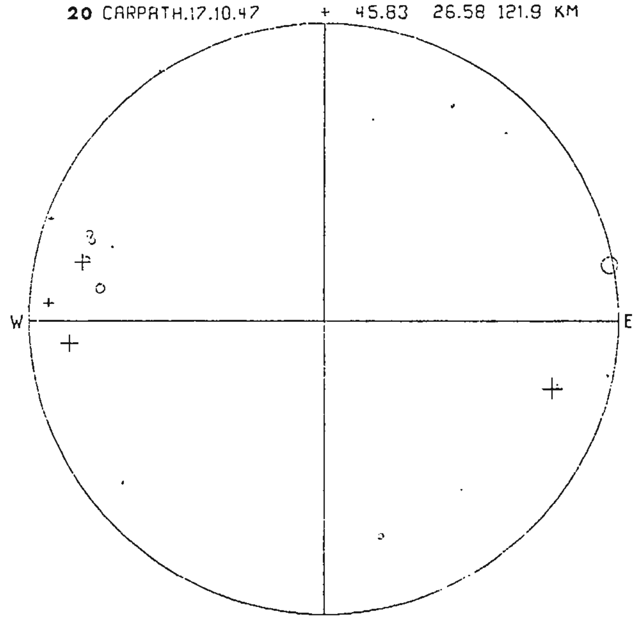
18 CARPATH.03.10.46 + 45.47 26.33 116.8 KM



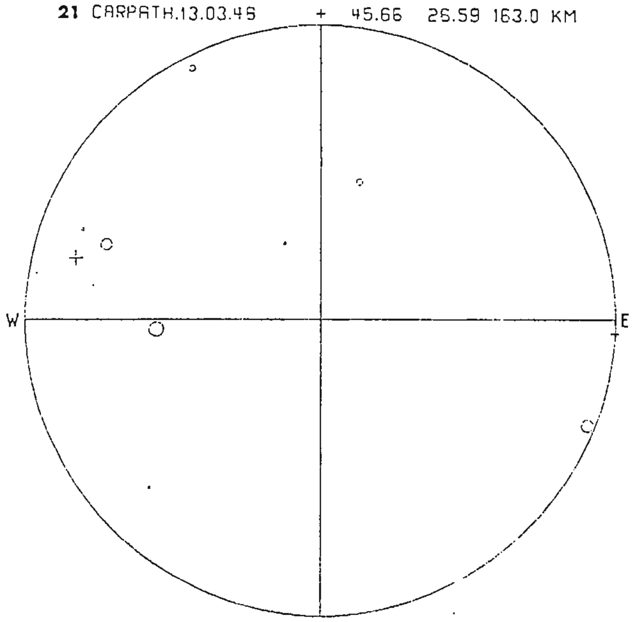
19 CARPATH.03.11.46 + 45.60 26.30 130.9 KM



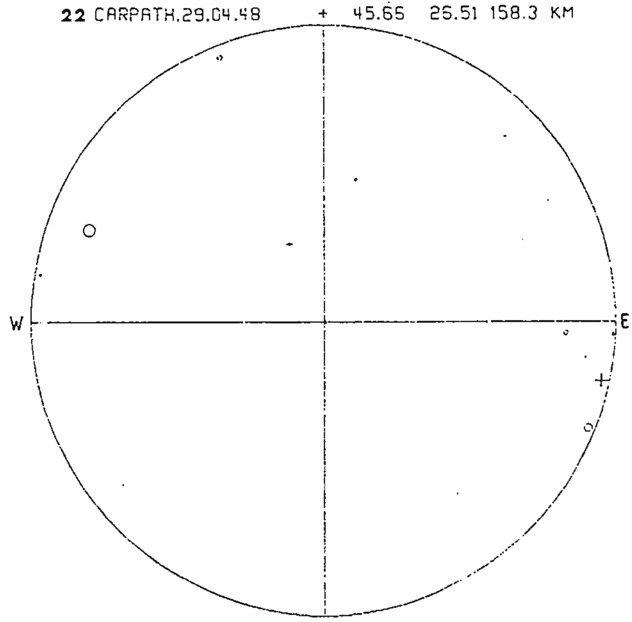
20 CARPATH.17.10.47 + 45.83 26.58 121.9 KM



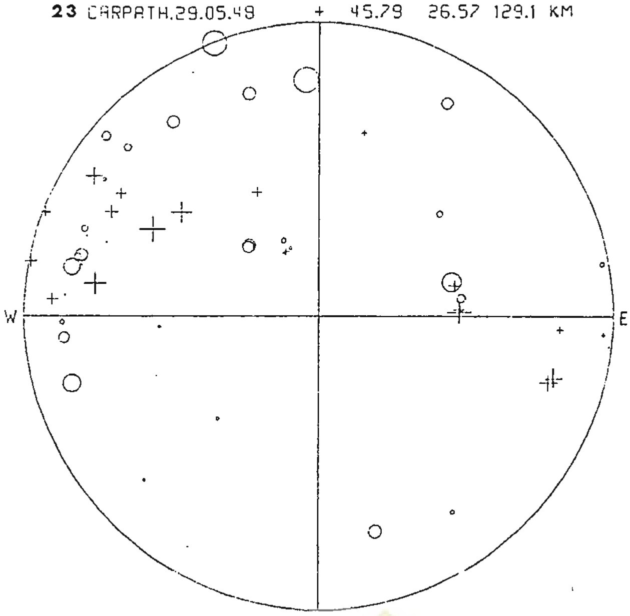
21 CARPATH.13.03.48 + 45.66 26.59 163.0 KM



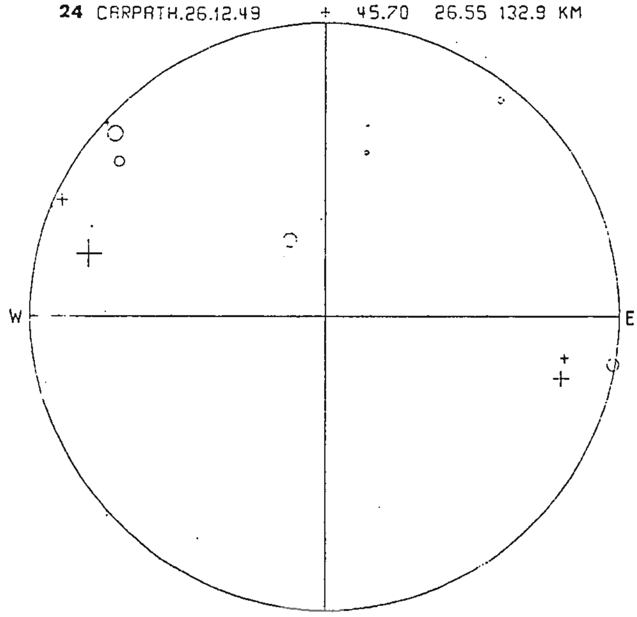
22 CARPATH.29.04.48 + 45.66 26.51 158.3 KM



23 CARPATH.29.05.49 + 45.79 26.57 129.1 KM



24 CARPATH.26.12.49 + 45.70 26.55 132.9 KM



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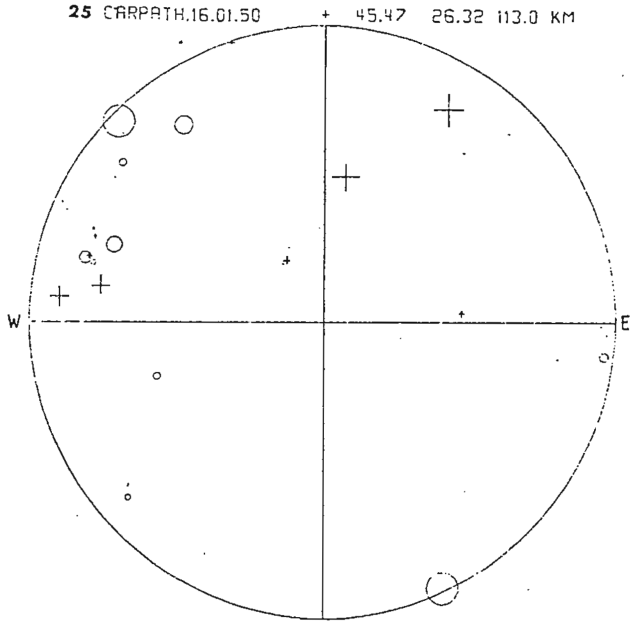

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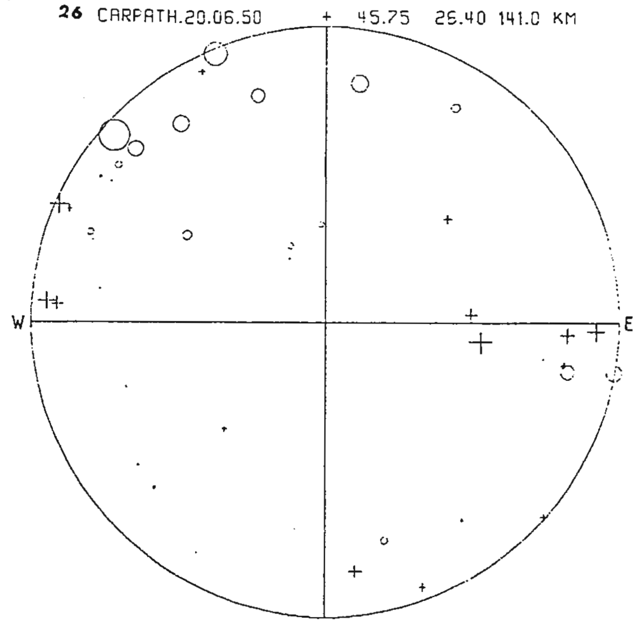

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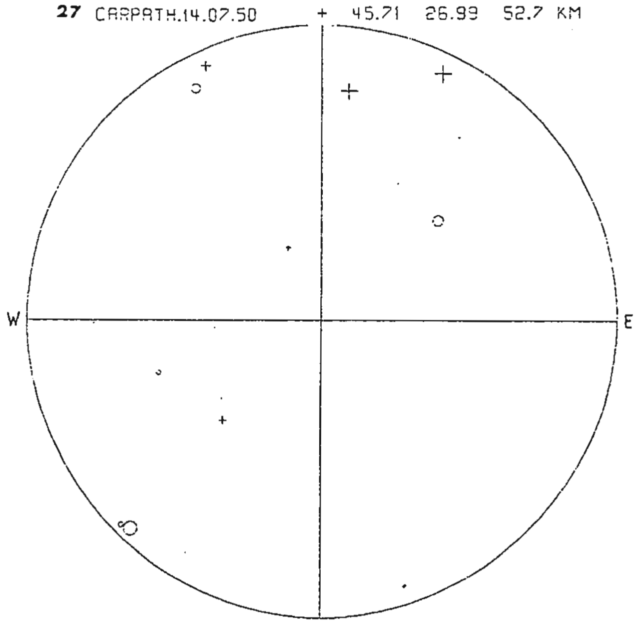

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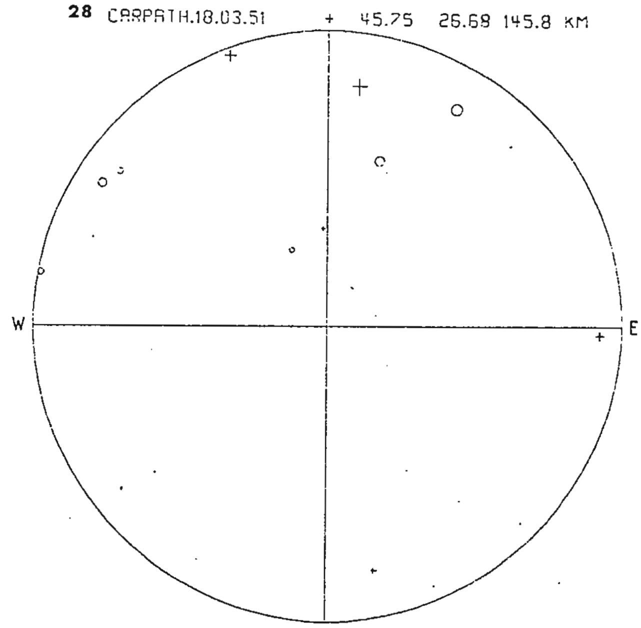

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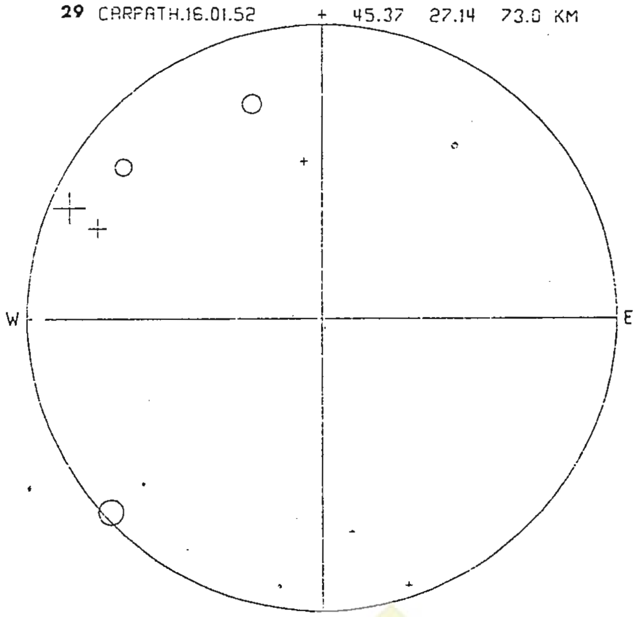

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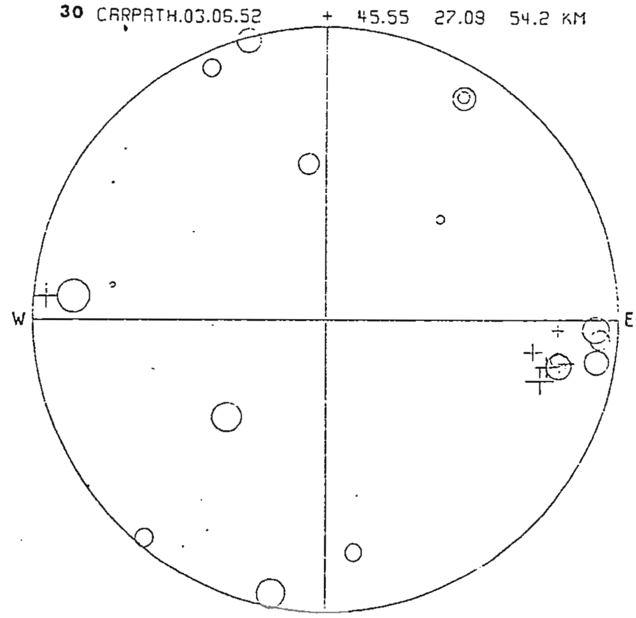

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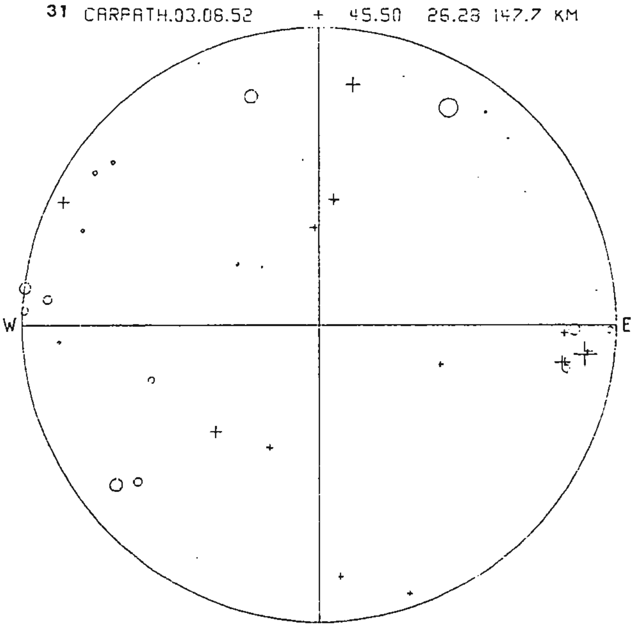

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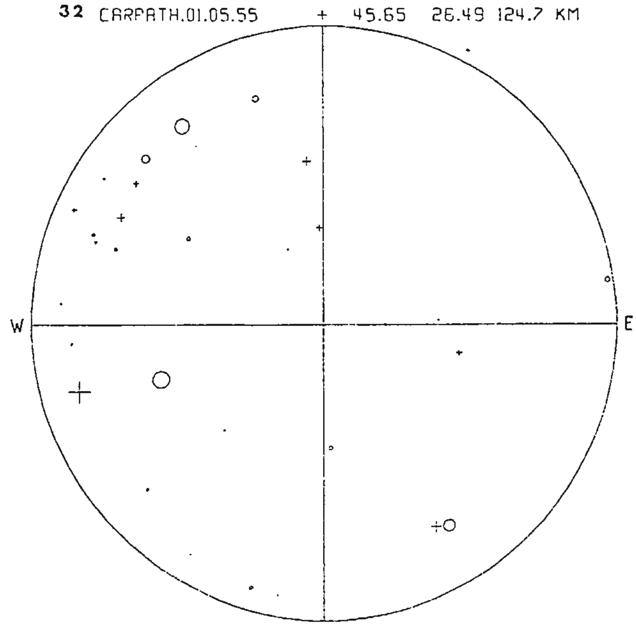

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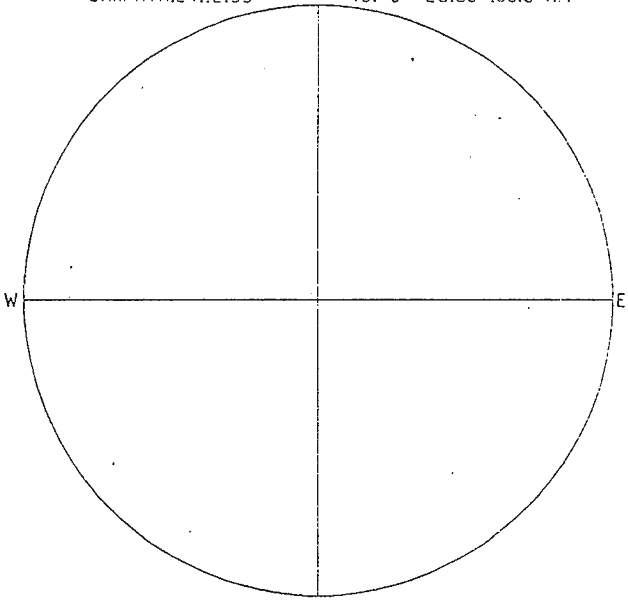

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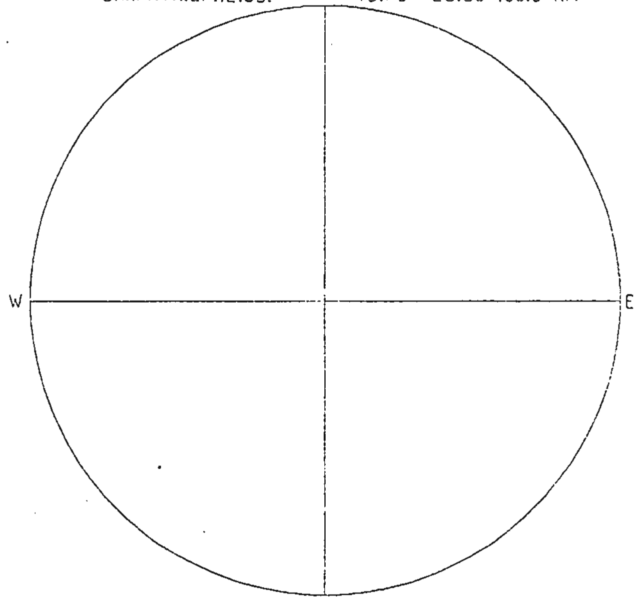

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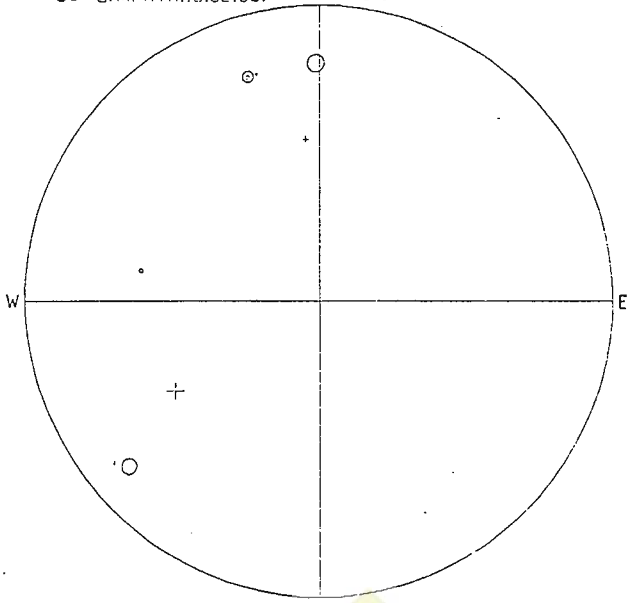

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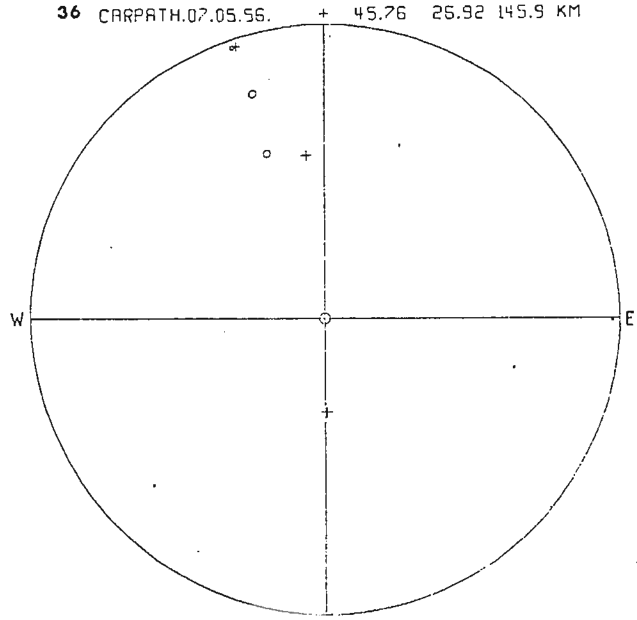

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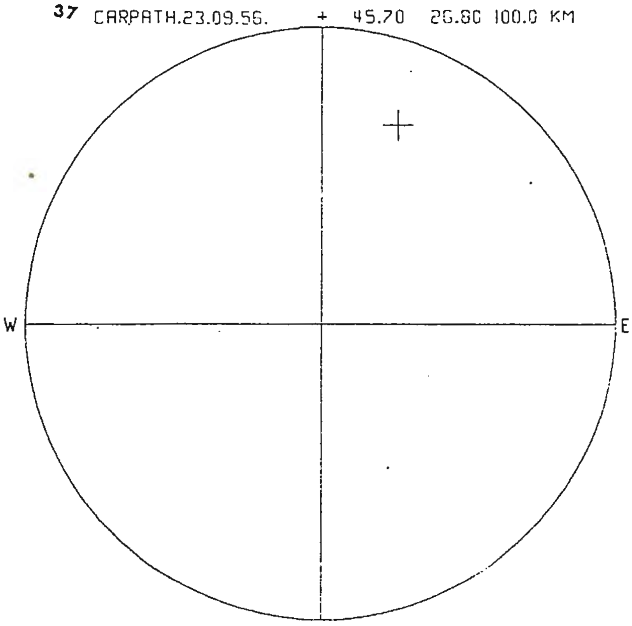

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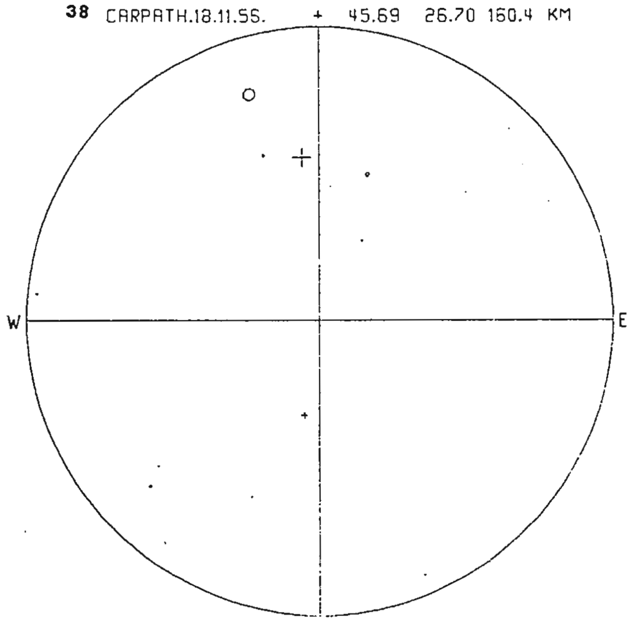

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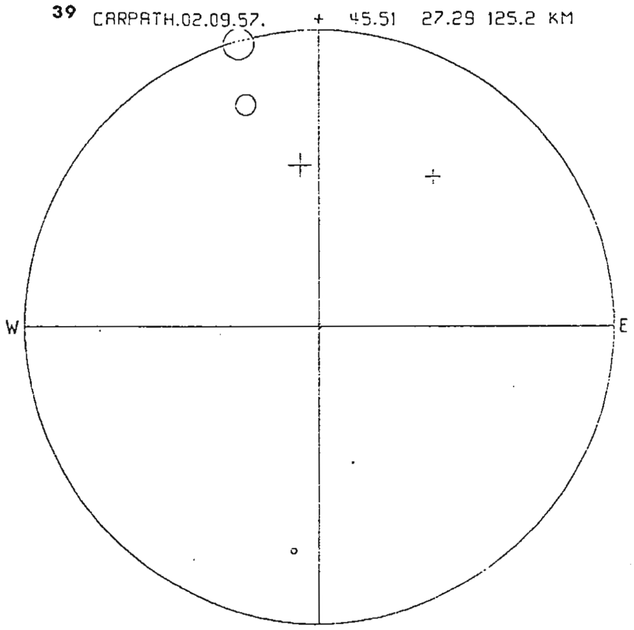

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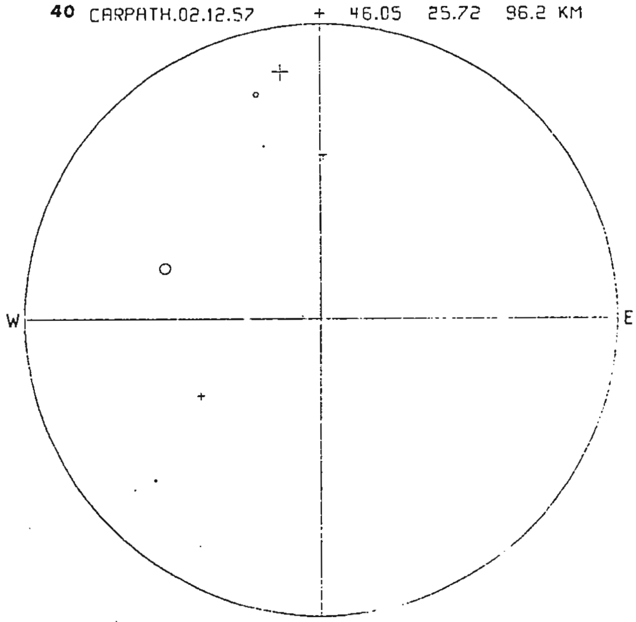

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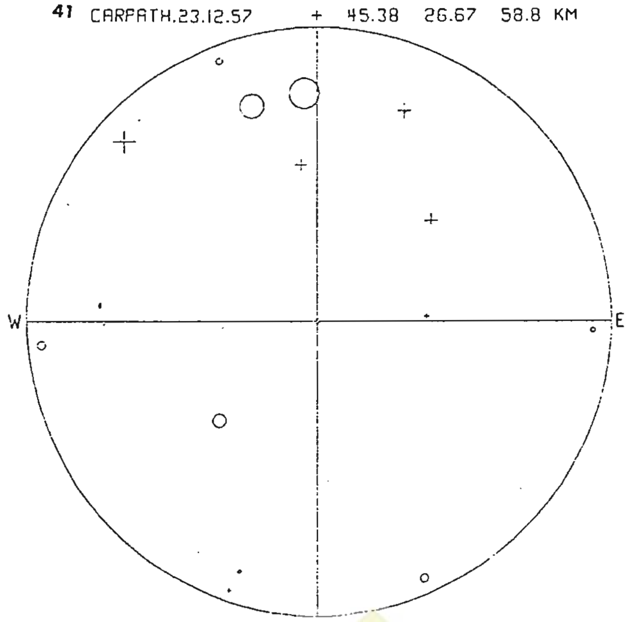

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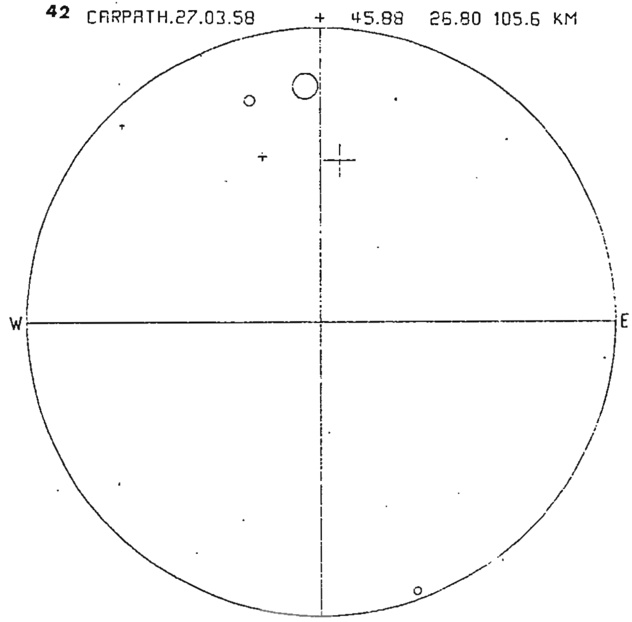

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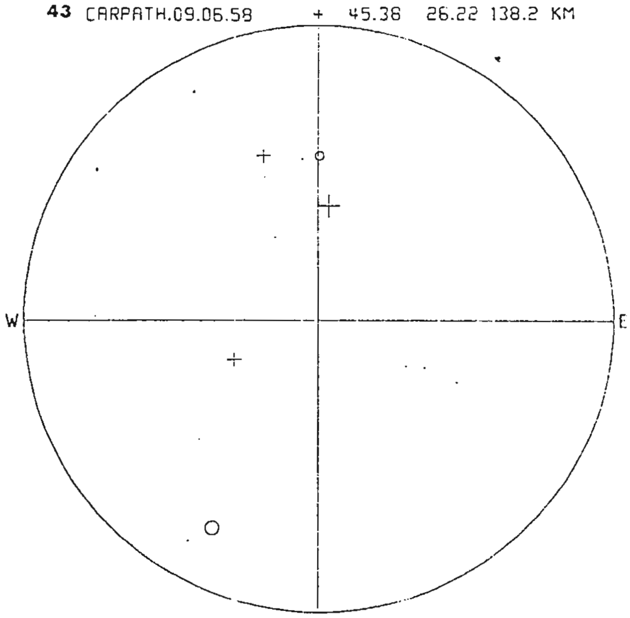

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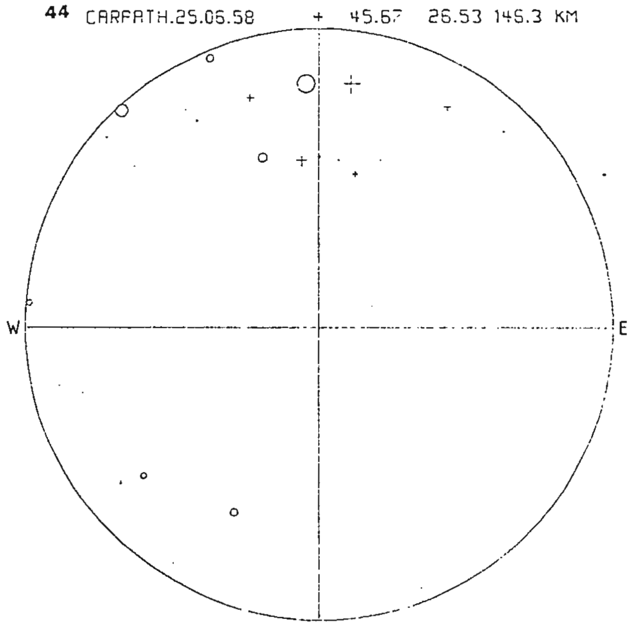

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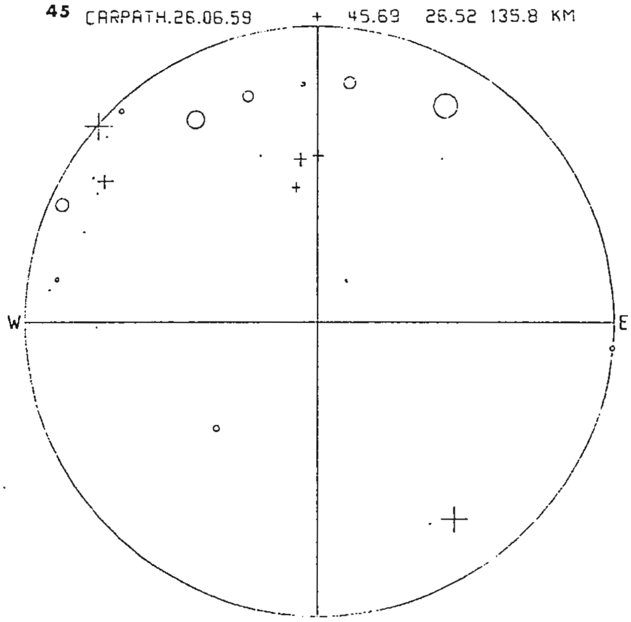

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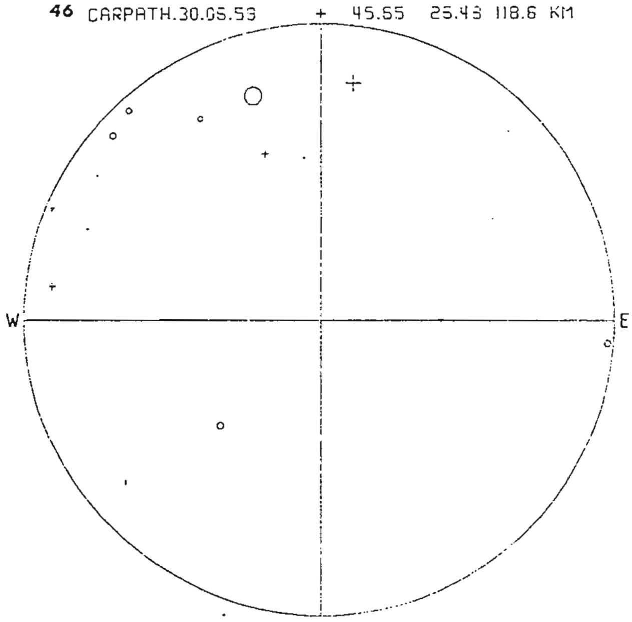

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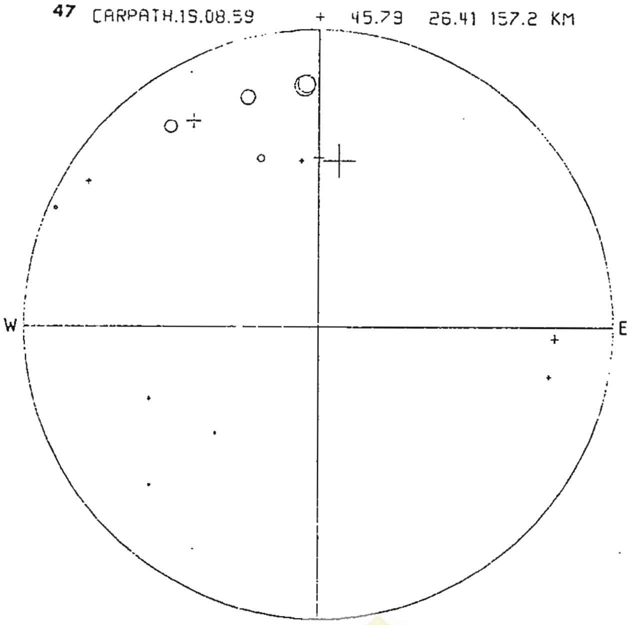

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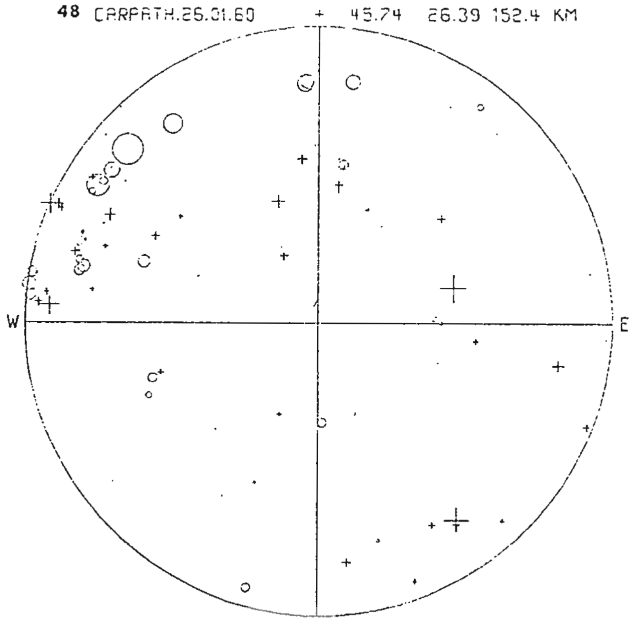

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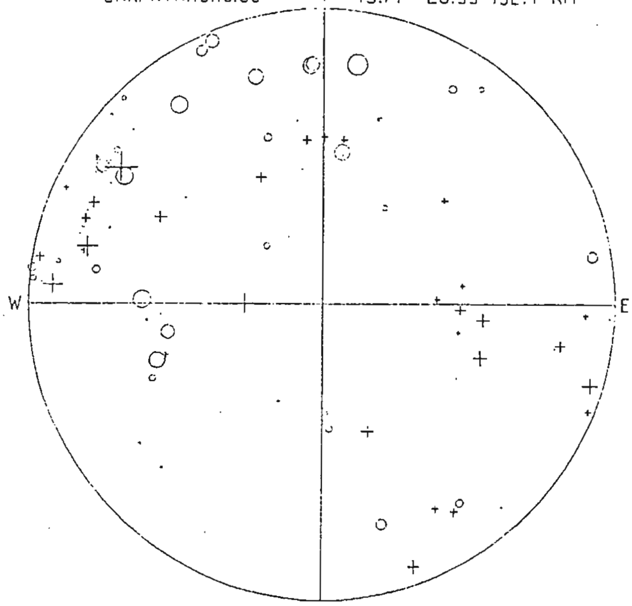

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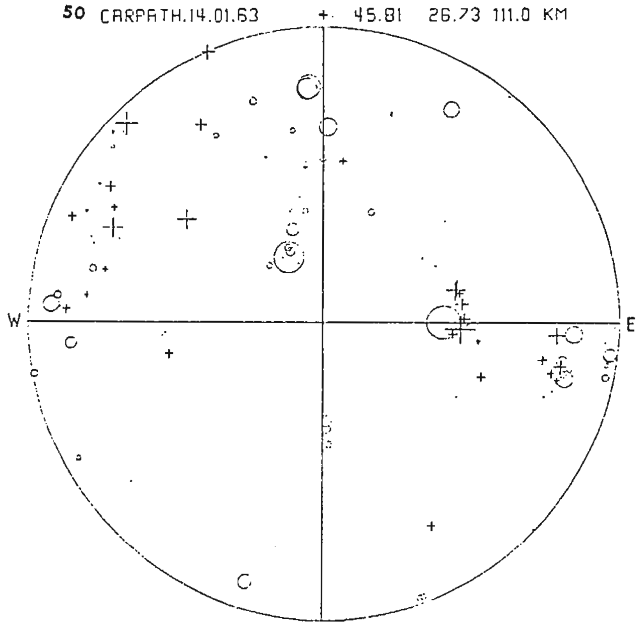

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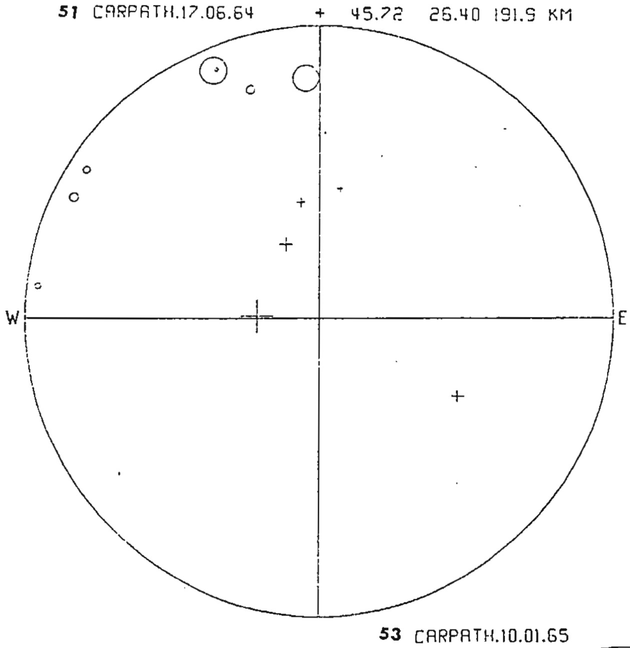

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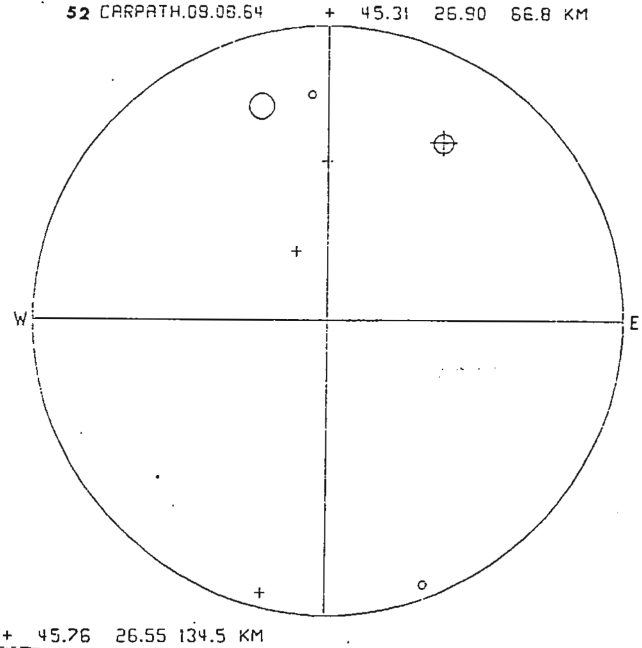

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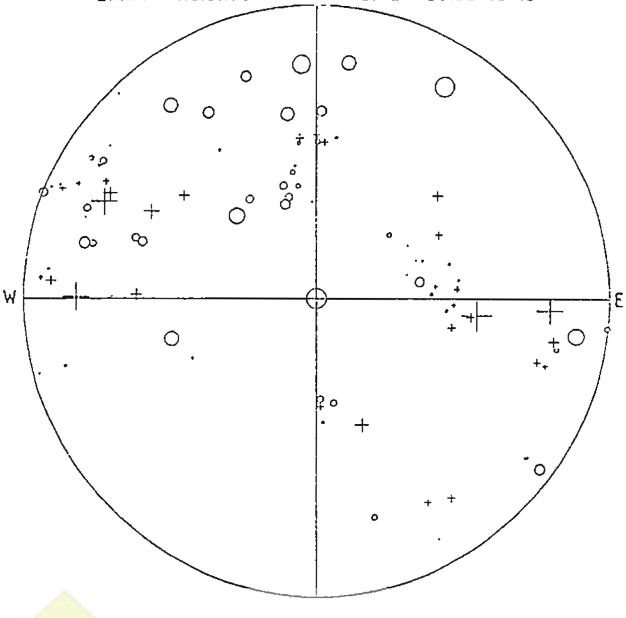

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1965	"Magnetic Dating in Archaeology" (Contemporanul, 17, 967, Bucharest, 1965)
1966	"Offshore Archaeology" (Viata Studenteasca, 11, 3 (168) Bucharest 18 Jan 1966)
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1984 UK, Southern North Sea - the influence of the Zechstein salt diapirism of the Quadrant 44 in the Southern North Sea's Gas area on the depositionof the Lower Triassic Bunter sands and shales of blocks 44/8 and 44/9 and 44/14 (Norsk Hydro, UK)

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1985 France, Paris Basin, - Hydrocarbon Prospectivity of the Paris Basin - a regional Study (Celtic Petroleum, Sussex, UK)

1985 SW France, Hydrocarbon Prospectivity of the Aquitaine Basin - a Regional Study (Celtic Petroleum, Sussex, UK)

1985 Morocco, Mid-east Atlantic - Stuctural, Stratigraphic plays, Economic and Risk analyses of the Aaiun basin , offshore the former Spanish Sahara, within the Plate Tectonic regional framework (Article published in the Oil and Gas Journal). (Geco Norway and ONAREP, Rabat, Morocco)

1985 SE France, (French Alps), The Geological and Geophysical evaluaton of the Prospectivity in the "Bonneville" M295 licence with a view of a farm-out proposal by Eurafrep (Imperial Continental Gas Association, London and Stateside France, Paris, Francea)

1985 SE France - a critical evaluation of Total's exploration activities, as operator for a international consortium of oil companies in the "Valencole" and "Draguignan" permits (onshore SE France)(Imperial Continental Gas Association, London and Stateside France, Paris, France)

1985 Northern Tunisia, Gabes Basin, - a spatial distribution of Cainozoic and Pre-Cainozoic prospects of the Gabes Basin, North and South Kairouan permits, Northern Tunisia - Seismic sequence analysis, structural geology analysis, Integration of geological and geophysical data, regional well-correlation - a critical review of past exploration activity intended to appraise past dry holes and generate new prospects (Kuwait Foreign Petroleum Company Tunisia and Kufpec UK, London)

1985 Central Mediterranean: Plate Tectonic model & basin evolution of the region Comprised between Central-North Tunisia (Gabes Basin) and the central Mediterranean (Offshore Southern Sicily) - its relevance to the local hydrocarbon structure (Kuwait Foreign Petroleum Company Tunisia and Kufpec UK, London)

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1986 SE France - a critical evaluation of Total's farm-out proposal, as operator for a international consortium of oil companies in the "Albaron-Crau" permit (Imperial Continental Gas Association, London and Stateside France, Paris, France)

1986 SE France, "Vauvert-Gallician" M350 permit a critical evaluation of Eurafrep's farm-out proposal, (Imperial Continental Gas Association, London and Stateside France, Paris, France)

1986 France, Paris Basin, The "Brie" P202 permit, - geological and geophysical data overview (Celtic Petroleum, Sussex, UK)

1986 France, Paris Basin, The Geological and Geophysival evaluation of the Prospectivity in the "Cher"and "La Claise" licences with a view of relinquishment proposals (Imperial Continental Gas Asociation, London, Stateside France, Paris, France)

1986 France, Western Mediterranean, Narbonne Maritime's N252 permit - Evaluation and quality analysis of Union Texas' farm-out proposal (Imperial Continental Gas Association, London, UK)

1987 Romania - Hydrocarbon Prospectivity and Geological Basin Study (Celtic Petroleum, Sussex, UK)

1988 Bulgaria - Hydrocarbon Prospectivity and Geological Basin Study (Celtic Petroleum, Sussex, UK)

1988 Yugoslavia - Hydrocarbon Prospectivity and Geological Basin Study (Celtic Petroleum, Sussex, UK)

1989 Hungary - Hydrocarbon Prospectivity and Geological Basin Study (Celtic Petroleum, Sussex, UK)

1989 Poland - Hydrocarbon Prospectivity and Geological Basin Study (Celtic Petroleum, Sussex, UK)

1990 Czech Republic and Slovakia - Hydrocarbon Prospectivity and Geological Basin Study (Celtic Petroleum, Sussex, UK)

1990 Austria - Hydrocarbon Prospectivity and Geological Basin Study (Celtic Petroleum, Sussex, UK)

1990 Albania - Northern Greece, Southwest Yougoslavia, the Adriatic and Ioanian seas and Italy - Hydrocarbon Prospectivity and Geological Basin Studies (Celtic Petroleum, Sussex, UK)

1990 Belize - wildcat appraisal, Hydrocarbon Prospectivity and Geological Overview (Celtic Petroleum, Sussex, UK)

1991 Black Sea and Environs - Hydrocarbon Prospectivity and Geological Basin Study (Celtic Petroleum, Sussex, UK)

1992 Black Sea and Environs -Geodynamic Study and Plate Tectonics Reconstruction (Celtic Petroleum, Sussex, UK)

1993 Ukraine - Hydrocarbon Prospectivity and Geological Basin Study (Celtic Petroleum, Sussex, UK)

1993 Geodynamic Model and Basin Reconstruction of the Black Sea and Environs (Celtic Petroleum, Sussex, UK)

1994 Carpathians - Hydrocarbon Prospectivity and Geological Basin Study (Celtic Petroleum, Sussex, UK)

1995 Pannonian, Vienna and Transylvanian Basins - Hydrocarbon Prospectivity and Geological Basin Studies (Celtic Petroleum, Sussex, UK)

1996 Moesian Platform - Hydrocarbon Prospectivity and Geological Basin Study (Celtic Petroleum, Sussex, UK)

1997 "The Vrancea Overthrust - Hydrocarbon Prospectivity" (Celtic Petroleum, Sussex, UK)

LECTURES & PRESENTATIONS

C. Roman: Lectures and Presentations:

1968 "A Study of Magnetic Properties of Rocks from Ore Deposits of Complex Sulphides in Eastern Carpathians and Dobrogea". (NATO Advanced Studies Institute on Palaeogeophysics, School of Physics, University of Newcastle upon Tyne, April, 1968)

1970 "Plate Tectonics in Romania: a case in Development". (European Seismological Meeting, Luxembourg, September, 1970).

1970 "A Space Distribution of Hypocentres in the Carpathians". (Dept. of Geodesy and Geophysics, University of Cambridge).

1971 "Seismicity in Romania and Plate Tectonics". (Dept. of Geology and Dept. of Geophysics and Meteorology, Goethe University, Frankfurt/Main, Germany, January 1971).

1971 "Seismicity of the Eurasian Plate". (Dept. of Environmental Sciences, University of East Anglia, January 1971).

1972 "Seismotectonics". (United Kingdom Atomic Energy Authority, Seismological Laboratory, Blacknest, February 1972)

1972 "Seismicity in Central Asia". (Dept. of Geodesy and Geophysics, University of Cambridge, March 1972).

1972 "Seismicity of the Alpine Belt with Special Reference to the Carpathians and the Himalayas". (Dept. of Geology, University of Cambridge, April 1972).

1972 "Plate Boundaries across Continental Crust'. (Dept. of Geophysics and Dept. of Geology, Imperial College, London, November 1972).

1972 "Sur la Limite des Plaques Lithospheriques dans la Croute Continentale". (Laboratoire de Géophysique and Laboratoire de Petrolgie, University of Liége, Belgium, December 1972).

1973 "Rigid Plates, Buffer Plates, Sub-Plates". (Dept. of Geology and Mineralogy, University of Oxford, May 1973).

1973 "Rigid Plates, Buffer Plates, Sub-Plates". (School of Physics, University of Newcastle upon Tyne).

1973 "Alpine Orogeny and the Problem of Plate Boundaries across Continental Crust". (European Geophysical Meeting, Zurich, September 1973).

1976 "Plate Tectonics and Hydrocarbon Distribution in Romania". (Dept. of Geology, University of Cambridge, October 1976).

1976 "Living with Earthquakes". (129th talk at the Sedgwick Club, University of Cambridge, October 1976).

1977 "Plate Tectonics and the Spatial Distribution of Oil and Gas Fields". (Petroleum Exploration Society of Great Britain, London, April 1977).

1978 "The Future of Romania's Oil Production". (First European Petroleum and Gas Conference, Amsterdam, May 1978).

1979 "Identifying Strike-slip Faults". (Exploration Dept., Statoil, Stavanger, April 1979).

1979 "Pitfalls in the Seismic Interpretation of Strike-slip Faults". (Norsk Petroleum Forening, talk sponsored by Statoil, Stavanger, May 1979).

1979 "Pitfalls in the Seismic Interpretation of Strike-slip Faults". (C.F.P., Total, Paris, June 1979).

1979 "La Norvege vue en trois dimensions". (Compagnie Francaise des Petroles, Total, Paris, Annual Meeting, December 1979).

1983 "Krieging and the Deep Structure",(Petroleum Exploration Society of Great Britain, London).

1983 "Krieging and the Deep Structure",(Norwegian Tectonic Group, The University of Oslo, May 1983).

1986 "Offshore Aauin Basin, Western Sahara - New Exploration Opportunities",(Institute of Directors, London).

1990 "The Oil and Gas Fields of Eastern Europe". (Petroleum Society of Great Britain, London, June 1990).

1991 "Romania: What future for Geology?"
(AGID Meeting - The Progress of the Earth Sciences in Eastern Europe and Possible Needs for Technical Co-operation: Geological Society, Burlington House, London,27th March 1991).

1991 "Romania's Oil Industry" (Joint World Bank and International Finance Corporation Meeting at the World Bank, Washington DC., April 1991).

1992 "Plate Tectonics of the Black Sea"
(International Symposium of the Black Sea region, Ankara, 1992)

1993 " The Roman Lectures"
(Exploration Case Histories World-wide - a series of ten lectures delivered as Visiting Professor of the University of Bucharest to the Faculty of Geology and the Dept. of Geophysics, Bucharest, May 3-14, 1993)

1993 "Black Sea Geodynamics"
(A joint lecture delivered to the Romanian Academy Institute of Geodynamics, The Romanian National Committee of Geodesy & Geophysics and the Romanian Academy of Science, Bucharest, may 1993)

1993 "A Romanian exploring Five Continents"
(The Romanian Geophysical Society, Bucharest, May 1993)

1993 "Aaiun Basin Hydrocarbon Potential"
(Romanian Geological Survey, Bucharest, May 1993)

1993 "Black Sea Geodynamics and the Local Hydrocarbon Structure"
(Dallas Geological Society, sponsored by ARCO, Dallas, June 1993)

1998 "Black Sea Geodynamics and the Local Hydrocarbon Structure"
(Geological Society London and the Petroleum Exploration Society of Great Britain, London, June 1998)

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