LEON KNOPOFF, Ph.D., D.h.c.

Research Professor of Physics and Geophysics
and Research Musicologist
University of California, Los Angeles

EDUCATION

B.S. California Institute of Technology (Elect. Engrg.) cum laude	1944
M.S. California Institute of Technology (Physics)	1946
Ph.D. California Institute of Technology (Physics and Mathematics) cum laude	1949

ACADEMIC

Research Prof. of Geophysics, Institute of Geophysics, UCLA, and Research Prof. of Physics, Department of Physics, UCLA	1994-2011
Prof. of Geophysics, Institute of Geophysics, UCLA, and Prof. of Physics, Department of Physics, UCLA	1961-1994
Prof. of Geophysics, Institute of Geophysics, UCLA	1959-1961
Assoc. Prof. of Geophysics, Institute of Geophysics, UCLA	1957-1959
Research Associate in Geophysics, Institute of Geophysics, UCLA	1950-1957
Assoc. Professor of Physics, Miami University, Oxford, Ohio	1949-1950
Asst. Professor of Physics, Miami University, Oxford, Ohio	1948-1949
Professor of Geophysics, California Institute of Technology	1962-1963
Research Musicologist, Institute of Ethnomusicology, UCLA	1963-
Visiting Professor, Cambridge University	1960-1961, 1976-1977, 1986-1987
Visiting Professor, University of Karlsruhe	1966
Visiting Professor, Harvard University	1972
Visiting Professor, University of Chile	1973
Visiting Professor, University of Trieste	1984
Visiting Scientist, Laboratorio per lo studio delle dinamiche di grandi massi, Venice, Italy	1970

HONORS

Docteur Honoris Causa, Université Louis Pasteur, Strasbourg	2004
Honorary Professor, Institute of Geophysics, China Earthquake Administration, Beijing	2004
Fellow, Selwyn College, Cambridge University, 1986-1987	elected 1986
Member, National Academy of Sciences	elected 1963
Fellow, American Academy of Arts and Sciences	elected 1965
Member, American Philosophical Society	elected 1992

HONORS, Continued

The (H.F. Reid) Medal of the Seismological Society of America	1990
Gold Medal, Royal Astronomical Society	1979
Emil Wiechert Medal, Deutsche Geophysikalische Gesellschaft	1978
Golden Badge Award, European Geophysical Society	2001
NSF Senior Postdoctoral Fellow	1960-1961
Guggenheim Foundation Fellow	1976-1977
Fellow, American Association for the Advancement of Science	elected 1964
Fellow, American Geophysical Union	elected 1962
Honorary member, Seismological Society of America	elected 1990
Honorary member, Phi Beta Kappa	elected 1996
(Foreign) Associate, Royal Astronomical Society	elected 2003
Canadian International Cooperation Year Medal	1965
Listed in *Top 1000 Scientists: From the Beginning of Time to 2000 AD* by Philip Barker, Universities Press, Hyderabad, 2002	
Festschrift volume: ***Geophysical Journal International*** v. **143**, (2000) pp. 279-498.	
Honorary Symposium, UCLA	Sept. 14, 2000
Honorary Seminar, Strasbourg	June 15, 2004
Harold Jeffreys Lecturer, Royal Astronomical Society	1977
Beno Gutenberg Lecturer, American Geophysical Union	1992
Sidney Chapman Memorial Lecturer, University of Alaska	1988
Distinguished Geophysics Lecturer, Texas A & M University	1990
UCLA Faculty Research Lecturer	1972
Outstanding teaching awards, Physics Department, UCLA	1987-88, 1992-93, 2 awards in 1995-96
Oral History, American Inst. of Physics	1990
Oral History, UCLA	2003

REFERENCE LISTINGS

Who's Who in America
Who's Who in Science and Engineering
American Men and Women of Science
International Who's Who
Who's Who in the West
Who's Who in American Education
Who's Who in Science
McGraw-Hill Modern Scientists and Engineers
Chambers' Dictionary of Scientists
Dictionary of International Biography
Men of Achievement
Who's Who in Technology
Directory of American Scholars

ADVISORY BOARDS

Editorial Board, ***Science***	1985-1990
Educational Advisory Board, J.S. Guggenheim Foundation	1989-2006
Seismic Hazard Committee, City of Anchorage, Alaska	1999-2002

PUBLICATIONS

Author and coauthor of 232 scientific papers in refereed journals.

Author and coauthor of 134 other publications, including original papers in non-refereed journals, book chapters, and other reports and reviews.

Books:

The Crust and Upper Mantle of the Pacific Area
L. Knopoff, C.L. Drake and P.J. Hart, editors,
Geophysical Monograph No.**12**, American Geophysical Union,
xi+522 pp, 1968.

The World Rift System
L. Knopoff, B.C. Heezen and G.J.F. MacDonald, editors,
Tectonophysics, Vol. **8**, Nos. 4-6, 309 pp, 1969.

The Nature of the Solid Earth
E.C. Robertson, J.F. Hayes and L. Knopoff, editors,
McGraw-Hill Book Co., N.Y., xiv+671 pp, 1972.

The Upper Mantle
A.R. Ritsema, editor, K. Aki, P.J. Hart and L. Knopoff, assoc. editors,
Elsevier Publishing Co., Amsterdam; xii+644 pp., 1972.

Instabilities in Continuous Media
L. Knopoff, V.I. Keilis-Borok and G. Puppi, editors,
Contributions to Current Research in Geophysics, vol. **12**, Birkhäuser Verlag, Basel, 210 pp, 1985.

Earthquake Prediction, The Scientific Challenge
L. Knopoff, editor, Proc. National Acad. Sciences, vol. **93**, 3719-3842, 1996.

TEACHING

39 research students awarded Ph.D.
40 postdoctoral scholars from 17 countries

FIELDS OF EXPERTISE

Earthquakes, physics of earthquakes and of earthquake prediction, nonlinear dynamical systems, complex systems analysis, fracture mechanics and fracture dynamics, elastic wave propagation, structure of the earth's interior, plate tectonics, measurement of the earth tides at the South Pole, dating of ancient pottery by thermoluminescence, musical perception, etc.

MEMBERSHIP IN PROFESSIONAL SOCIETIES

American Association for the Advancement of Science (fellow)
Seismological Society of America (honorary member)
American Geophysical Union (fellow)
American Physical Society
Royal Astronomical Society

EDITORIAL BOARDS

Reviews of Geophysics and Space Physics	1963-1970
Tectonophysics	1973-1996
Wave Motion	1979-1984
Bolletino di Geofisica	1981-1986
Editor, Nonlinear Processes in Geophysics	1994-2000
Associate Editor, Journal of Geophysical Research	1996-2000

UNIVERSITY SERVICE (partial list)

Director, Institute of Geophysics and Planetary Physics, UCLA	1972-1986
Physics Department, UCLA, Graduate Admissions Officer	
Physics Department, UCLA, Chair, Space Assignment Committee	
Chair, University of California Systemwide Committee on Seismic Risk	1985-1989
Joint Chancellor's/Senate Committee on Seismic Risk, UCLA	1983-1988
Faculty Research Lectureship Committee, Academic Senate, UCLA Frequent Service since 1972, Occasionally Chair	
Budget Committee, Academic Senate, UCLA	
Committee on Computing, Academic Senate, UCLA (Chair, 1970-71)	1970-1972

SERVICE (Selected):

Secretary-General, International Upper Mantle Project	1963-1971
Chair, U.S. Upper Mantle Committee	1963-1971
Chair, International Union of Geodesy and Geophysics (IUGG) Committee on Mathematical Geophysics	1971-1975
Vicechair, IUGG Committee on Mathematical Geophysics	1975-1979
Organizer of Biennial Conferences of Committee on Mathematical Geophysics, IUGG	1972-1986
U.S. National Committee for the Geodynamics Project	1971-1975
U.S. National Committee for the International Union of Geodesy and Geophysics	1973-1977
Chair, U.S. Committee for the International Association of Seismology and Physics of the Earth's Interior (IASPEI)	1973-1977
Ad Hoc Committee on Seismology and Aftershocks, U.S. Atomic Energy Commission	1972
Governor's Earthquake Council, State of California	1972-1974
Committee on Earthquake Prediction, U.S. National Academy of Sciences	1973
U.S. Working Group on joint US-USSR Earthquake Prediction Program	1973
Earthquake Studies Advisory Panel, U.S. Geological Survey	1973-1977
Panel to Review US-USSR Scientific Exchanges, U.S. National Academy of Sciences, Board on International Scientific Exchange	1975
Senior Advisory Committee, Incorporated Research Institutions for Seismology	1985-1989
Steering Committee, Southern California Earthquake Center	1991-1999

PERSONAL

Place of Birth: Los Angeles, California
U.S. Citizen
Married to Joanne Van Cleef Knopoff; three children:
Katherine (Katie) Knopoff Wadley, Rachel A. Knopoff, Michael V.C. Knopoff

ADDRESS

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SUMMARY OF ACHIEVEMENTS

Knopoff and his students, postdoctoral scholars and colleagues have made seminal and pioneering discoveries and contributions in a wide variety of fields:

Nonlinear earthquake dynamics

- Studies of earthquake occurrence as nonlinear science
- Nonlinear dynamics of rupture in self-organization of earthquakes
- Highly popular model for earthquake and seismicity simulations
- Contributions to models of self-organized criticality
- Importance of geometrical inhomogeneities on self-organization of earthquakes
- Magnitude distribution of tectonically driven earthquakes is not self-similar
- Importance of subcritical creep on clustering of seismicity and to earthquake prediction
- Resurrection of the single-couple model of earthquake faulting

Earthquake Statistics

- Solution of the cause of the universality of the Gutenberg-Richter and Omori laws of earthquake distributions
- The inverse Omori law for the rate of occurrence of earthquake foreshocks
- Power law distribution of epicenter spacings
- Long-range correlations among large and intermediate-magnitude earthquakes

Geophysics

- Regionalization of the continental upper mantle into shields, rifts, stable younger regions
- Relatively cool "keel" beneath ancient continental shields to depths of about 400km
- Discovery of ultralow velocity channel under the Pacific Ocean which is a zone of decoupling the convecting lithosphere from the middle mantle
- Attenuation of seismic waves: Earth's mantle above 400km depth is much more attenuating than mantle below 400km.
- Attenuation of seismic waves: Introduced specific attenuation factor Q into common seismological language
- Observation of 14-day and 28-day tides at South Pole
- Quantum mechanics calculations of the properties of metals at core pressures

Theoretical Elastodynamics

- Scattering and diffraction of elastic waves
- Properties of inhomogeneous materials, especially as a function of crack density

Archaeology

- Co-discoverer of thermoluminescence method of dating of ancient pottery

Music

- Studies of musical perception

HIGHLIGHTS OF THE RESEARCH OF LEON KNOPOFF

I. Theoretical Seismology

Knopoff has contributed to the theory of elastic wave propagation in inhomogeneous media with applications to seismology. This provided an understanding of scattering, diffraction, surface wave propagation. These results have application to the understanding and reduction of noise on seismograms, which are those often very large wiggles on the records that prevent the observation of desired signals on seismographic recordings for both earthquake and petroleum exploration purposes.

Gilbert and Knopoff published a theory of the diffraction of short wavelength elastic waves by curved obstacles with special reference to the diffraction and focusing of seismic waves by the core of the earth [24, 37]. This work laid the foundation for later studies of propagation in the presence of curved subduction structures in the earth and of waveform tomography in a spherical earth by Helmberger and colleagues.

Garbin and Knopoff published the first calculation of the average elastic properties of an elastic solid permeated by cracks [177, 190, 191]. Chatterjee, Mal and Knopoff published the first exact calculation of the elastic properties of a composite to second order in the concentration [224, 230]. The latter results are of importance in the field of non-destructive testing of materials permeated by hidden flaws. These papers showed that self-consistent methods of calculation were incorrect in the second order in concentration of extended inhomogeneities. Extension to the percolation limit at high densities was made by Davis and Knopoff [365].

Knopoff published a representation theorem for the full elastic wave equation. Buried in that solution was the demonstration that the displacement in the far field radiation from faulting is proportional to the velocity of slip on a fault [8].

Hudson and Knopoff published the theory of the scattering by statistical distributions of obstacles in a layered earth, and the nature of signal-generated seismic noise [80, 88, 90, 94].

II. Attenuation of Sound in Solids and in the Earth

Knopoff studied and analyzed the phenomenology and mechanisms for attenuation of elastic waves in solid materials [67]. Knopoff and MacDonald showed that the observation that the Q of solids at small strains is independent of the frequency is due to nonlinearity [11, 31]. Knopoff showed that attenuation of sound waves in solids, as measured in the laboratory, is due to non-linear grain-boundary sliding. Knopoff made the assumption that properties of attenuation in the laboratory could be extended to the earth's interior, and inverted surface wave and free mode observations to show that the upper mantle of the earth had a much greater attenuation than the lower mantle [67]. Hence the upper mantle may be closer to its melting point than the lower mantle. The use of the parameter Q to describe attenuation in the earth has become commonplace since Knopoff's paper with that abbreviated title [67].

III. The geophysical inverse problem

In the inverse problem, one wishes to determine the properties of an inaccessible region from measurements at selected locations (usually) on its surface. Knopoff showed that the geophysical inverse is non-unique, i.e. that one can never determine the properties of the inaccessible region with precision, and hence that it is incumbent upon geophysicists to indicate the range of uncertainties in their interpretations [40]. Keilis-Borok, Knopoff and a number of students developed the hedgehog method of inversion, which directly specified the class of solutions consistent with the data [178], and which is still occasionally used in the problems of geophysical inversion. Knopoff and Jackson constructed a solution to the problem of overparameterization of structure, i.e. how to fit the detailed structure (of the earth) with insufficient data [161].

Knopoff published the first computational solution to the fault-plane problem [41] and with Teng, the first computational solution to the travel-time problem [74], the first concerned with deriving the mechanism at the source of an earthquake and the second to determining both the location of an earthquake and the earth's structure between the earthquake and the seismograph.

IV. Observations of long-period earthquake surface waves

Knopoff made the first installation of temporary long-period seismic networks for the purpose of making synoptic measurements of earthquake surface waves [81, 82, 98]. Using these observations, he performed inversion of phase relations for surface wave observations to derive regional interior structure of the earth (see below). As far as known, Knopoff, Mueller and Pilant were the first to perform digital processing of long-period seismograms [81]. Nakanishi, Slichter and Knopoff developed an ultralong-period seismometer [205], installed at the South Pole and still in use today.

V. Interior Structure of the Earth

The seismic low-velocity channel at a depth of about 100 km and deeper in the earth, was identified and classified; this classification permitted the discovery of significant differences in the upper mantle of the earth between oceanic and continental provinces, the latter further divisible into shields, younger stable continents and active regions. Knopoff identified an almost global universality of upper mantle structure for these types of regions from local studies; this formed the basis for regionalizations used in later global studies.

Knopoff showed that continental upper mantle structure could be divided into three broad types, which are the ancient shields, tectonically inactive regions of intermediate age, and tectonically active regions including rifts [162]. This result depended on regional studies carried out with Biswas [178], Panza [236], Schlue [163], Fouda [189], Mueller [81].

Knopoff and his students Leeds, Kausel and Schlue, showed that the upper mantle in the Pacific had a waveguide with extraordinarily low S-wave velocities, fully 10 to 15% lower than at comparable depths in the shields, and that this must surely represent a zone of decoupling between the motion of the oceanic lithosphere and the deeper mantle [184, 202, 215]. The thickness of the oceanic layer was about 100 km at its oldest part. Implying the existence of very high temperatures at shallow depths under the Pacific; such high temperatures could only arise because of slip of the uppermost 100 km of the Pacific structure over the substrate during convection. From this and other information derived from surface wave analysis, the lithosphere is inferred to slide over the lower mantle over a decoupling layer which is the low-velocity channel. The low-velocity channel under the Pacific Basin is a zone of partial melting. The low-velocity zone is probably caused by partial melting, and the upper boundary of the channel is on the melting solidus.

Except for the purely oceanic Pacific and Nazca Plates, all major tectonic plates were discovered to have a very deep root or keel under the continental shields, extending to depths as great as 400 km, and hence there must be a large viscous drag force on these plates. These deep keels are zones of cooling, having cooled from the surface downward, and represent a major thermal constraint on models of convection in the earth's mantle [162, 276]. For example, part of North America and the Atlantic are joined in a common plate whose slip is retarded by the American keel.

Wielandt and Knopoff found that the structure under the East Pacific Rise has anomalous low velocities to a depth of at least 400 km and if there is a phase transformation at this depth, it must be significantly elevated under the Rise, thereby implying that convection in the mantle penetrates to at least this depth [262].

During the course of the work on surface waves, methods were developed with Biswas [140], Schwab [138, 149, 160] and Panza [168, 192], to synthesize seismograms by studying methods of superposition of higher modes of surface waves. To do this Knopoff developed an efficient method for solving problems of elastic waves in multilayered media [53]. Panza has applied these techniques with much success to the study of the strong ground motions observed in the near-focus region of large earthquakes, with relevance to the problems of response of buildings during earthquakes.

VI. Earthquake Statistics

The universality of the log-linear regularity of the Gutenberg-Richter magnitude distribution law suggests universality of process. Nevertheless, the strong geometrical heterogeneity of fault zones worldwide suggests that there should be large variations in these distributions from seismic region to region. Assumptions of universality derived from the distributions in complete catalogs, composed of both aftershocks and mainshocks, have been attributed to the properties of mainshocks. Knopoff has resolved the incompatibility [356] by showing that the aftershock population dominates the catalogs and that the statistical properties are mainly those of the aftershocks, which are in their turn mainly associated with the few largest earthquakes. The universality of the aftershock process has been shown to be due to the universality of the fragmentation of the neighborhood of major earthquake faults. The range of fragmentation distances is approximately 3 km in Southern California; the overwhelming majority of aftershocks are found in these low-strength zones. The distribution for mainshocks in Southern California with magnitudes greater than about 5 does not follow the standard Gutenberg-Richter law; scale-independent models are not applicable.

Knopoff's early belief was that the subject had advanced sufficiently to permit construction of models that could be used in either an earthquake prediction sense or in a risk analysis sense. To do this, Kagan and Knopoff began to study the statistics of earthquakes systematically and carefully. One of the important results from this work was the discovery that the barriers and asperities to earthquake rupture are geometrical in origin (rather than of geological origin), and the three-dimensional character of this geometry could be identified; in other words, earthquake faults are not plane surfaces!

Most small earthquakes occur in a damage zone nearby an earthquake fault. This zone is the residue of past epochs of major faulting. Thus most small earthquakes are not genuine predictors of subsequent instability on a major fault. However they do play the role of a stress gauge, and as such are a predictor of the onset of critical states on major faults.

Kagan and Knopoff were the first to establish the statistical validity of the 1/t law of increase of number of foreshocks before a main shock [227]. They showed that there is migration of earthquake epicenters, even among large earthquakes [204]. In the case of the largest earthquakes, there are correlations on a time scale of several years and at distances of up to 2500 km. These correlations were shown to be statistically significant. Thus even large earthquakes cluster!

Kagan and Knopoff were the first to identify the universal statistical regularities of spatial distributions of earthquakes. They identified the universal power law for the distribution of the distance between earthquake epicenters. Thus earthquake epicenters have a scale-independent self-similar distribution, with implications for the geometry of faults [244]. His recent work shows that this result is a property mainly of aftershocks which dominate the statistics.

Keilis-Borok and Knopoff showed that a certain class of intermediate sized earthquakes almost always precedes the strongest earthquakes in Southern California as well as in other parts of the world [241]. The time interval between the predecessor and successor earthquakes is about 3 years and the distances between them may be as large as several hundred km. Molchan showed that these correlations are statistically significant.

Kilston and Knopoff showed that there is a statistically significant correlation between the phases of the moon and strong earthquakes in Southern California. The cause of these correlations may be ocean loading off the Southern California coast [275]. These correlations are absent in the case of smaller earthquakes in Southern California, probably because most of the smaller earthquakes are aftershocks.

VII. Statistical Earthquake Prediction

Knopoff and Kagan incorporated geometry and creep-induced time delays into a stochastic model of a complex earthquake source, and succeeded in modeling short-term clustering of individual earthquakes as well [254]. They were able to apply this theoretical model of rupture with stochastic elements (which has only a small number of parameters) to earthquake risk analysis, i.e. to estimate the probabilities of occurrence of future earthquakes, at least on the short time-scale [295]. This work represents the first time a physical theory with a very small number of adjustable parameters has been applied to the extrapolation of an earthquake catalog for the purposes of prediction. As a gambling proposition, this short-term predictor offers about 1000:1 odds that about 40% of strong earthquakes will be identified in specified space and time windows; the time scale is from a few hours to a few days.

Keilis-Borok and Knopoff developed a systematic phenomenology for earthquake prediction. These systematic techniques were applied to the prediction in advance of the Armenian and Loma Prieta earthquakes [312]. The Loma Prieta earthquake was predicted to have a magnitude greater than 6.4, within a time window of four years starting from midsummer 1986, and in a roughly rectangular region about 600 km in linear dimensions, with a success rate of about 80%.

Knopoff and colleagues have shown that 28 out of 31 strong earthquakes in Northern and Southern California are preceded by a widespread increase in the rate of occurrence of intermediate-magnitude earthquakes over a time interval of from 2 to 10 years; the time interval is dependent on the size of the future great earthquake. However no such increase is found for small earthquakes [339]. What was most remarkable in the result was that seismicity was drastically reduced over a very long range compared with the size of the earthquake rupture. The dimensions of the future earthquake are so small compared with the size of the region of anomalous precursory activity, that a significant change in our attitude toward understanding earthquake stress fields is needed.

VIII. Modeling the Seismic Source and the Theory of Earthquake Prediction

Knopoff has been working on the development of a comprehensive theory of earthquakes, to explain from first principles the phenomenology of precursory quiescence, earthquake swarms, sudden increases in precursory seismicity, aftershocks, foreshocks. Knopoff has shown that there is a strong coupling of earthquake occurrence to modern developments in non-linear science, including the trappings of chaos, strange attractors, etc. There are four basic ingredients of any model of earthquake occurrence: plate tectonics to restore the energy dissipated in earthquakes, stress redistribution because of fracturing, precursory creep processes producing time delays between the times critical stresses are reached and the times to fracture, and the influences of inhomogeneity in physical properties, which are almost wholly geometrical.

Burridge and Knopoff constructed the first numerical model of a nonlinear dynamical system to simulate seismicity and faulting. In the last 12 to 14 years, this model has become a favorite of many groups for simulating self-organization and chaos in the earthquake dynamical system [92]. It has been cited many hundreds of times, both in the physics and geophysics literature on earthquake clustering. This paper has been a beacon in the non-linear modeling community for modeling earthquake processes.

Knopoff has argued that earthquake seismicity as a self-organizing process cannot be modeled on the basis of quasistatic models of fractures alone, but that the dynamics of the rupture process is extremely important in the analysis. His position is that what goes on during the brief moments of the rupture cannot be ignored, neither in the effects on human life and structures, but also in terms of the state of stress of the earth after the earthquake. He therefore began an extensive program of analysis of rupture dynamics, especially in the presence of the irregular geometry of faults. Irregular geometry can be modeled as a local increase in friction (fracture threshold) [350]. In the presence of fluctuating fracture thresholds, cracks grow subsonically; the fracture criteria must be applied on the moving edge(s), which are a form of Stefan problem [174, 259, 280, 359]. Of concern in these problems has been the decay of friction from the static state to the dynamic state and these have been explored analytically [357] as well as numerically [332].

Knopoff has applied these ideas to the problems of seismicity as a self-organizing system and has found that geometry is a pervasive influence on pattern formation, and indeed can lead to instabilities in the self-organization [326]. The properties of these systems are completely unlike systems that are popularly assumed to be spatially homogeneous. The postulate of spatial homogeneity has been popularized because of the scale-independence implicit in the Gutenberg-Richter distribution law of earthquake magnitudes. However Knopoff has shown that the scale-independence is not a property of the main-shock population that the modeling of (future) events is intended to simulate, but is instead a property of aftershocks, which dominate the statistics [356]. He has found that the mainshock population has a major transition scale at around earthquake magnitude 5, thus indicating a varying physics of rupture for earthquakes smaller and larger than these magnitudes.

In two widely quoted papers, Knopoff calculated the energy to be released in sliding on a source model of an earthquake [12], and Burridge and Knopoff [70] identified the equivalence between body forces and seismic dislocations (this work was independent of Maruyama's, but Maruyama published shortly before B+K; the B+K paper is the more often quoted, and is significantly more general). Among other results, it was established rigorously that a seismic source will radiate seismic waves with a double couple focal mechanism.

Knopoff observed that pre-shock creep is an extremely important influence affecting clustering of earthquakes. (If earthquakes do not cluster in time and in space, there is no hope for earthquake prediction; the problem is to unravel the observations of earthquake sequences to determine the mode of clustering.) Yamashita and Knopoff, and Chen and Knopoff have been concerned with physical models of stress corrosion in producing clustering such as aftershocks [296] and foreshocks [302]; they have even been able to reproduce complete clustering histories that start with earthquake swarms, followed by an extended period of seismic quiescence, followed in turn by foreshocks and a main shock [299]. Such sequences have been suggested as possible precursory histories before great earthquakes. Yamashita and Knopoff demonstrated that the intermediate-term, intermediate-magnitude clustering of earthquakes before very strong ones, is caused by some form of accelerated precursory creep, a two-dimensional spatial distribution of earthquake faults and a fluidized environment for faulting. This can generate precursory spatio-temporal quiescence under the proper geometry of a strongly faulted region [324].

Knopoff and his students have shown that the Gutenberg-Richter magnitude-frequency law is not a property of self-organization of stresses on a single fault, but is instead a characteristic of seismicity on a complex fault system. In their model, characteristic earthquakes and highly fluctuating spatiotemporal distributions take place in the presence of a distribution of inhomogeneity of the frictions that regulate faulting. Thus the earthquake self-organizing system is not in a critical state, heterogeneity is important in the evolutionary process for earthquakes, and spatial localization of earthquakes is a consequence of the geometry [325].

The phenomenology of precursory intermediate-magnitude, intermediate-time clustering before strong earthquakes (see above) has forced us to change our way of thinking about earthquake mechanism. Knopoff has proposed that the phenomenology can only be explained if it is supposed that the fault system of California is permanently permeated by water at high enough pressure to reduce the sliding friction to virtually zero. The fault is prevented from slipping by an array of very strong patches of "glue". When the earth is at a critical state for the onset of subcritical creep, the smaller patches begin to degrade by stress corrosion at an accelerated rate, and ultimately these break in intermediate-magnitude earthquakes. When the strong event occurs by the same mechanism of stress corrosion, but this time in the fracture of a major patch, the precursory process is switched off because the stresses are redistributed to great distance by triggered sliding along the fluidized faults that adjoin the patch(es).

IX. Equations of state of earth-forming materials

MacDonald and Knopoff published a confirmation of the Birch hypothesis that the outer core is not pure iron [17, 30]. To do this, as far as is known, they were the first to use shock wave data to identify the deep composition of the earth. They proposed silicon as an alloying agent for the core; this early proposal was much criticized, but has recently re-emerged as a popular candidate. The problem is important for understanding how the earth condensed out of the primitive solar nebula. Bukowinski and Knopoff used quantum mechanics to determine the properties of iron [198] and potassium [219] at core pressures and found that a proposed outer shell electronic transition in potassium might justify its use as an alloying agent in the core; there are other, geophysical reasons why it is not a suitable alloying agent, but the potassium transition cannot be excluded on structural grounds.

X. Earth Tides

From observations made at the South Pole, Rydelek and Knopoff published the first accurate, direct observation of the amplitude and phase of the 14- and 28-day lunar earth tide [260, 266]. From the phase lead of the 14-day tide observed at the South Pole, they were able to infer that the worlds oceans are not equilibrium oceans at these periods [303], i.e. that the tides cannot be calculated from static attractions of sun and moon, but must instead be derived from a dynamical theory, even though these periods are far from the period of resonance of the oceans.

XI. Thermoluminescence Method for Dating Ancient Pottery

Kennedy and Knopoff were the first to date ancient pottery by thermoluminescence techniques [35, 36]. Without significant modification, it is the procedure that hundreds of workers in archaeology and art history are using today.

XII. Systematic musicology, Economics and Linguistic Structure

Knopoff and Hutchinson have published a number of quantitative tools for doing melodic stylistic analysis [218, 225, 230, 238, 255, 271, 298]. They have established perceptual alphabets for melodic temporal pattern recognition and have identified temporal windows for short term pattern recall. They have established that human physiological processes have strong influences on the way in which a society develops language.

In an application of his work on nonlinear dynamics of earthquakes, Knopoff has shown that personal decision making, psychological influences, and creativity have an inordinate influence on economic structure and as a consequence economic prediction by formal time-series analysis is not justified; economic systems are open systems and the human influence cannot be ignored.

In the area of written language as a complex system, grammatical structure, i.e. long-range correlation, plays a vital role in its self-organization, and hence nearest-neighbor structural analysis, such as through Markov process analysis, is not justified. In the area of musical structure, these problems are even more intricate because several sensory detectors (of tonal duration, pitch and loudness) are all in interactive play simultaneously [305].