ΔΗΜΟΣΙΑ ΣΥΝΕΔΡΙΑ ΤΗΣ 12ΗΣ ΙΟΥΝΙΟΥ 2003

ΑΝΑΚΟΙΝΩΣΗ

Ὁ Ἀκαδημαϊκὸς κ. **Γεώργιος Κοντόπουλος** παρουσιάζει τὴν ἐργασία τοῦ καθηγητοῦ κ. Β. Κ. Παπαζάχου, μὲ τίτλο **Chaos in seismology and earthquake prediction**.

Εἰσαγωγή. Ἡ θεωρία τοῦ χάους ἔχει πολλὲς ἐφαρμογὲς σὲ διαφόρους κλάδους τῆς Φυσικῆς, ἀπὸ τὴ μελέτη τῶν μορίων μέχρι τὴ σπουδὴ τοῦ Σύμπαντος.

Μία ἐνδιαφέρουσα ἐφαρμογὴ τῆς θεωρίας αὐτῆς ἀναφέρεται στὴ σεισμολογία. Ὁ κ. Παπαζάχος, ὁμότιμος καθηγητὴς τῆς Γεωφυσικῆς στὸ Πανεπιστήμιο Θεσσαλονίκης, στὴ μελέτη του αὐτὴ παρουσιάζει διάφορες ἐφαρμογὲς τῆς θεωρίας τοῦ χάους ποὺ μποροῦν νὰ ὁδηγήσουν στὴ στατιστικὴ πρόγνωση τῶν σεισμῶν.

Ἡ λιθόσφαιρα τῆς γῆς ἀποτελεῖ ἕνα ἐξαιρετικὰ πολύπλοκο μὴ γραμμικὸ σύστημα. Ἡ συμπεριφορὰ τοῦ συστήματος αὐτοῦ δὲν εἶναι τυχαία, ἀλλὰ παρουσιάζει φαινόμενα τάξης καὶ χάους. Σημειώνω ὅτι τὸ χάος εἶναι διαφορετικὸ ἀπὸ τὴν τύχη. Ἀκολουθεῖ ὡρισμένους νόμους, καὶ γι' αὐτὸ τὸ καλοῦμε «ντετερμινιστικὸ χάος».

Νέες ἰδέες στὴ Σεισμολογία. Τὰ τελευταῖα 15 χρόνια πολλὲς ἔννοιες τῆς θεωρίας τοῦ χάους εἶχαν ἐφαρμογὴ στὴ σεισμολογία.

Σὲ πολλὲς περιπτώσεις ἐμφανίζονται «νόμοι δυνάμεως» (power laws), δηλαδὴ μία ὁρισμένη ποσότης δίνεται ὡς δύναμις μιᾶς ἄλλης ποσότητος. Τέτοια εἶναι ἡ σχέση τῆς συχνότητος τῶν σεισμικῶν ρηγμάτων μιᾶς περιοχῆς μὲ τὸ μῆκος τῶν ρηγμάτων. Ὁ ἐκθέτης τῆς δυνάμεως ὀνομάζεται «κλασματικὴ διάσταση». Ἕνας τέτοιος νόμος παρουσιάζεται στὰ fractals. Δηλαδὴ ἂν παρατηρήσουμε τὰ φαινόμενα σὲ μικρότερη καὶ μικρότερη κλίμακα βλέπουμε ὅμοια φαινόμενα σὲ κάθε κλίμακα. Τὰ φαινόμενα παρουσιάζουν αὐτοομοιότητα. Εἰδικότερα ἰσχύουν στὴν περίπτωση αὐτὴ ὁμάδες ἐπανακανονικοποιήσεως (renormalization groups) ποὺ δίνουν τὶς ἐξισώσεις ποὺ ἰσχύουν σὲ μιὰ ὁρισμένη κλίμακα μεγεθῶν μὲ μιὰ ἁπλὴ ἀλλαγὴ μεταβλητῶν ἀπὸ μιὰ ἄλλη κλίμακα μεγεθῶν.

Στὴ σεισμολογία χρησιμοποιήθηκαν ἁπλὰ μοντέλα ποὺ ἔχουν χαοτικὲς καὶ φρακταλικὲς ἰδιότητες. Τέτοια μοντέλα εἶναι (1) τὸ «μοντέλο ὀλισθαινόντων σωμάτων» (sliding block model), (2) τὸ μοντέλο τῆς ἀμμοβολῆς ἢ ἀμμοστοιβάδος (sand pile model), (3) τὸ μοντέλο πυρκαϊᾶς τοῦ δάσους (forest fire model), καὶ (4) τὸ μοντέλο τῆς κρίσιμης διήθησης (critical percolation model).

Ἀριθμητικὲς μέθοδοι προσομοιώσεως βασίζονται σὲ μοντέλα κυψελικῶν αὐτομάτων (cellular automata) ποὺ χρησιμοποιοῦν διακριτὲς μεταβλητὲς ἀντὶ γιὰ συνεχεῖς μεταβλητές. Οἱ τιμὲς τῶν μεταβλητῶν σὲ κάθε βῆμα καθορίζονται ἀπὸ τὶς τιμὲς τῶν μεταβλητῶν στὸ προηγούμενο βῆμα βάσει ὁρισμένων ἁπλῶν νόμων. Ἔτσι παρακολουθοῦμε ταχύτατα τὴν ἐξέλιξη τῶν συστημάτων μὲ ἠλεκτρονικοὺς ὑπολογιστές. Τέτοια μοντέλα δίνουν τὴν συμπεριφορὰ τῶν λιθοσφαιρικῶν ρηγμάτων κοντὰ σὲ ἕνα κρίσιμο σημεῖο ὅπως εἶναι ὁ ἑστιακὸς χῶρος κατὰ τὴ γένεση ἑνὸς σεισμοῦ.

Μιὰ βασικὴ θεωρία ποὺ χρησιμοποιεῖται σήμερα στὶς σεισμολογικὲς μελέτες εἶναι ἡ θεωρία τῆς «αὐτοοργανούμενης κρισιμότητος» (self-organized criticality). Σύμφωνα μὲ τὴ θεωρία αὐτὴ ἡ λιθόσφαιρα βρίσκεται τὸν περισσότερο χρόνο σὲ κατάσταση ὁριακῆς εὐσταθείας. Δηλαδὴ μιὰ μικρὴ διαταραχὴ μπορεῖ νὰ τὴν καταστήσει ἀσταθῆ καὶ νὰ προκαλέσει σεισμό. Ὁ σεισμὸς μπορεῖ νὰ ἔλθει σύντομα, ἀλλὰ μπορεῖ νὰ παρουσιασθεῖ μετὰ ἀπὸ μεγάλο χρονικὸ διάστημα. Ἑπομένως τὸ ὅτι τὸ σύστημα εἶναι σὲ ὁριακὴ εὐστάθεια δὲν σημαίνει ὅτι θὰ γίνει ἀμέσως σεισμός.

Στὶς θεωρίες αὐτὲς ὁ κύριος σεισμὸς θεωρεῖται ὡς ἕνα «κρίσιμο σημεῖο» (critical point) στὴν ἐξέλιξη τοῦ συστήματος. Σὲ ἕνα τέτοιο κρίσιμο σημεῖο οἱ ἰδιότητες τοῦ συστήματος ἀλλάζουν ἀπότομα. (Ἕνα γνωστὸ παράδειγμα κρισίμου σημείου εἶναι ἡ θερμοκρασία μεταβολῆς τοῦ νεροῦ σὲ ἀτμό. Στὴ θερμοκρασία αὐτὴ τὸ νερὸ χάνει ἀπότομα τὶς ἰδιότητες τοῦ ὑγροῦ καὶ γίνεται ἀέριο).

Ἡ μετάβαση τοῦ συστήματος στὸ κρίσιμο σημεῖο γίνεται μὲ ἕνα νόμο δυνάμεως. Ἔτσι, πρὶν ἀπὸ τὸν κύριο σεισμὸ ὑπάρχουν προσεισμικὰ φαινόμενα ποὺ ἐπιταχύνονται καθὼς πλησιάζουμε τὸν κύριο σεισμό.

Δημιουργία τῶν σεισμῶν. Ἡ βασικὴ αἰτία τῶν σεισμῶν εἶναι ἡ κίνηση τῶν τεκτονικῶν πλακῶν. Ἡ κίνηση αὐτὴ προκαλεῖ μιὰ βραδεία αὔξηση τῆς τάσεως ἑκατέρωθεν ἑνὸς ρήγματος. Ὅταν ἡ τάση ὑπερβεῖ ἕνα ὁρισμένο, ἀλλὰ ὄχι γνωστὸ ἐκ τῶν προτέρων ὅριο, ἡ συσσωρευμένη ἐνέργεια ἐκλύεται ὑπὸ μορφὴν σεισμικῆς ἐνεργείας, καὶ ἡ λιθόσφαιρα ἐπανέρχεται σὲ μιὰ νέα κατάσταση ἰσορροπίας, ἀλλὰ μὲ τὰ τμήματά της ἑκατέρωθεν τοῦ ρήγματος μετατοπισμένα (σχῆμα 1 τῆς ἐργασίας).

Ἡ κίνηση τῶν πλακῶν ὅμως συνεχίζεται. Ἔτσι δημιουργοῦνται νέες τάσεις ποὺ ἐκτονώνονται ἀπὸ νέους σεισμοὺς κ.ο.κ.

Θὰ ἔλεγε κανεὶς ὅτι τὰ φαινόμενα αὐτὰ ἔχουν μιὰ περιοδικότητα ποὺ θὰ ἐπέτρεπε τὴν πρόγνωση τῶν σεισμῶν. Ἐν τούτοις παρ' ὅλον ὅτι τὸ φαινόμενο εἶναι ντετερμινιστικό, ἡ συμπεριφορὰ τοῦ συστήματος εἶναι χαοτική. Δηλαδὴ μιὰ μικρὴ ἀλλαγὴ τῶν ἀρχικῶν συνθηκῶν προκαλεῖ μεγάλες μεταβολὲς στὴν ἐξέλιξη τοῦ συστήματος, καὶ αὐτὸ καθιστᾶ τὴν πρόγνωση μεμονωμένων σεισμῶν πρακτικὰ ἀδύνατη. Π.χ. μικρὲς διαφορὲς στὸ μῆκος ἑνὸς ρήγματος ἔχουν σημαντικὴ ἐπίδραση στὶς ἑπόμενες φάσεις τῆς τάσεως στὰ τμήματα τῆς λιθοσφαίρας ἑκατέρωθεν τοῦ ρήγματος.

Ἕνας πολὺ γνωστὸς νόμος στὴ σεισμολογία εἶναι ὁ νόμος Gutenberg-Richter

$$\mathrm{Log}N=a-bM$$

ὅπου N εἶναι ὁ ἀριθμὸς τῶν σεισμῶν μεγέθους ≥M καὶ a, b παράμετροι ποὺ ἐξαρτῶνται ἀπὸ τὴν περιοχή.

Στὸ σχῆμα 2 τῆς ἐργασίας δίδεται τὸ logN συναρτήσει τοῦ M: (a) σὲ ὁλόκληρη τὴ γῆ καὶ (b) στὰ Ἰόνια νησιά. Παρατηροῦμε ὅτι τὸ b καὶ στὶς δυὸ περιπτώσεις εἶναι πλησίον τοῦ 1, ἐνῶ τὸ a εἶναι πολὺ μεγαλύτερο στοὺς παγκόσμιους σεισμούς.

Ὁ κ. Παπαζάχος ἔδωσε μιὰ σχέση ποὺ δίνει τοπικὰ τὸ χρόνο T μεταξὺ διαδοχικῶν σεισμῶν μεγέθους μεγαλύτερου τοῦ M

$$\mathrm{Log}T=0.19M+0.33M_p+0.39\log m_0+q$$

ὅπου Mp εἶναι τὸ μέγεθος τοῦ προηγουμένου σεισμοῦ, m_0 ἐκφράζει τὴν ἐτησία σεισμικότητα τῆς περιοχῆς καὶ q εἶναι μιὰ σταθερά. Ἡ σχέση αὐτὴ εἶναι συμβατὴ μὲ τὸν νόμο Gutenberg-Richter καὶ ἐκφράζει τὴν μέση χρονικὴ ἀπόσταση μεταξὺ μεγάλων σεισμῶν.

Ὁ νόμος τῶν Gutenberg-Richter ἑρμηνεύεται σήμερα μὲ βάση τὴν ὑπόθεση τῆς κρίσιμης αὐτοοργανώσεως. Δηλαδὴ κάθε περιοχὴ ρηγμάτων εὑρίσκεται σὲ μιὰ κατάσταση ὁριακῆς εὐσταθείας. Μετὰ ἀπὸ κάθε σεισμὸ ποὺ ἀπελευθερώνει τὴ συσσωρευμένη ἐνέργεια, ἡ περιοχὴ ἐπανέρχεται σύντομα στὴν κατάσταση τῆς κρίσιμης αὐτοοργανώσεως.

Συνέπεια αὐτοῦ εἶναι ὅτι ἡ συχνότης τῶν σεισμῶν σὲ μιὰ εὐρεία περιοχή, σὲ συνάρτηση μὲ τὴν ἐνέργεια, ἀκολουθεῖ ἕνα νόμο δυνάμεως, ὅπως εἶναι ὁ νόμος Gutenberg-Richter. Ἡ ὑπόθεση αὐτὴ ἑρμηνεύει ἐπίσης τὴν ἐπαγόμενη ἀπὸ ἀνθρώπινες δραστηριότητες σεισμικότητα (φόρτωση τεχνητῶν λιμνῶν, ἄντληση πετρελαίου κ.λπ.).

Μεταξὺ τῶν προσπαθειῶν ἐφαρμογῆς τῆς θεωρίας τοῦ χάους γιὰ τὴν κατανόηση τῆς σεισμογένεσης εἶναι ἡ μοντελοποίηση τῆς προσεισμικῆς διαδικασίας ἡ ὁποία καταλήγει στὸν κύριο σεισμὸ ποὺ θεωρεῖται ὡς κρίσιμο σημεῖο. Τὸ μοντέλο αὐτὸ ἑρμηνεύει τὴν ἐπιταχυνόμενη διαδικασία γένεσης τῶν προσεισμῶν καὶ δημιουργεῖ ἔτσι ἀξιόπιστη θεωρητικὴ βάση γιὰ τὶς μεθόδους μεσοπρόθεσμης στατιστικῆς πρόγνωσης τῶν σεισμῶν ποὺ βασίζονται σ' αὐτὴ τὴν πρόδρομη ἐπιταχυνόμενη σεισμογένεση.

Πρόγνωση τῶν σεισμῶν. Ὁ κ. Παπαζάχος διακρίνει τρία εἴδη προγνώσεως. Τὴν βραχεία πρόγνωση (μερικῶν ἡμερῶν), τὴν μεσοπρόθεσμη (μερικῶν μηνῶν ἢ ἐτῶν) καὶ τὴν μακρὰ πρόβλεψη (δεκαετιῶν).

(1) Βραχεία πρόγνωση

Ἔγιναν πολλὲς προσπάθειες νὰ βρεθοῦν χαρακτηριστικὰ φαινόμενα ποὺ νὰ ἐπιτρέπουν τὴν πρόγνωση συγκεκριμένων σεισμῶν σὲ μιὰ ὁρισμένη περιοχή. Τέτοια φαινόμενα εἶναι σεισμολογικὰ (π.χ. προσεισμοί), ἠλεκτρομαγνητικὰ σήματα, μεταβολὲς τοῦ ἐδάφους, ἢ τοῦ ὕδατος τοῦ ὑπεδάφους κ.λπ.

Ὅμως ὅλες οἱ μέχρι τώρα προσπάθειες δὲν ἔφεραν πρακτικὰ ἀποτελέσματα. Οἱ προσπάθειες συνεχίζονται ἀλλὰ ἡ γενικὴ πεποίθηση εἶναι ὅτι μιὰ ντετερμινιστικὴ πρόγνωση συγκεκριμένων σεισμῶν εἶναι ἀδύνατη, δεδομένου ὅτι ἡ ἐξέλιξη τῆς λιθοσφαίρας εἶναι ἐν πολλοῖς χαοτική.

(2) Μεσοπρόθεσμη πρόγνωση

Τὸ μοντέλο τοῦ κρισίμου σημείου ἐπιτρέπει μιὰ στατιστικὴ πρόβλεψη τῶν σεισμῶν, δηλ. στὴν ἐκτίμηση τῆς σεισμικῆς ἐπικινδυνότητας μιᾶς περιοχῆς, ἀλλὰ μὲ ἀρκετὰ μεγάλη ἀβεβαιότητα στὸ ἐπίκεντρο καὶ στὸ χρόνο γένεσης τῶν σεισμῶν.

Π.χ. ἀπὸ τὴν στατιστικὴ τῶν σεισμῶν στὸ Β. Αἰγαῖο διαπιστώνονται κανονικότητες ποὺ ἐπιτρέπουν προβλέψεις γιὰ σεισμοὺς μεγαλύτερους τῶν M=6.4 Richter, μὲ ἀκρίβεια ± 100 km καὶ χρόνο ±1.5 ἔτη.

Ὁ κ. Παπαζάχος ὑπελόγισε τὴ συνολικὴ τάση S στὴν περιοχὴ τοῦ Β. Αἰγαίου τὸ 2000 καὶ ἔδωσε μιὰ καμπύλη τὴν ὁποία ἐπεξέτεινε καὶ στὸ μέλλον (Σχ.5 τῆς ἐργασίας). Μετὰ 10 μῆνες τὸ 2001 ἔγινε ἕνας σεισμὸς M=6.3 Richter στὰ ὅρια ποὺ προέβλεπε ἡ καμπύλη αὐτή. Δὲν θὰ μποροῦσε ὅμως νὰ γίνει μιὰ ἀκριβέστερη πρόβλεψη, οὔτε γιὰ τὸ ἐπίκεντρο, οὔτε γιὰ τὸ χρόνο τοῦ σεισμοῦ.

(3) Προβλέψεις μακρᾶς διαρκείας

Μποροῦν νὰ γίνουν μόνο στατιστικὲς ἐκτιμήσεις τῆς σεισμικῆς ἐπικινδυνότητος σὲ μεγάλες περιοχές, χρήσιμες γιὰ νὰ ληφθοῦν γενικὰ ἀντισεισμικὰ μέτρα, ἀλλὰ ὄχι προβλέψεις συγκεκριμένων σεισμῶν.

Τὸ συμπέρασμα εἶναι ὅτι στατιστικὲς μελέτες μποροῦν νὰ δώσουν στοιχεῖα γιὰ τὴ σεισμικὴ ἐπικινδυνότητα διαφόρων περιοχῶν, ἀλλὰ πρόγνωση συγκεκριμένων μεγάλων σεισμῶν δὲν εἶναι δυνατή.

Ὁ Ἀκαδημαϊκὸς κ. **Νικόλαος Ἀμβράζης** ἀναφέρει ὅτι ἡ ἐργασία τοῦ κ. Παπαζάχου εἶναι ἀξιόλογος. Ἂν καὶ μὲ περιορισμένα δεδομένα παρατηρήσεων ποὺ ἀφοροῦν ὡς ἐπὶ τὸ πλεῖστον τὸν Ἑλληνικὸ χῶρο, προσφέρει μία πρώτη ἔνδειξη χαώδους συμπεριφορᾶς τῆς σεισμικῆς δράσεως.

Ὁ Ἀκαδημαϊκὸς κ. **Νικόλαος Ἀρτεμιάδης** ἐρωτᾶ πῶς ὁ κ. Παπαζάχος ἐφαρμόζει τὴ θεωρία τοῦ Χάους γιὰ νὰ καταλήξει στὰ συμπεράσματά του.

Ὁ κ. **Γεώργιος Κοντόπουλος** ἀπαντᾶ τὰ ἑξῆς:

Ὁ κ. Παπαζάχος χρησιμοποιεῖ τὴ θεωρία τοῦ χάους σὲ ὁρισμένα μοντέλα ποὺ περιγράφουν τὴν ἐξέλιξη τῶν σεισμῶν καὶ καταλήγει σὲ προβλέψεις τῆς σεισμικῆς δραστηριότητας σὲ σχετικὰ μεγάλα χρονικὰ διαστήματα. Δὲν μπορεῖ ὅμως νὰ προβλέψει συγκεκριμένους σεισμούς.

Chaos in seismology and earthquake prediction, by B. C. Papazachos*, διὰ τοῦ Ἀκαδημαϊκοῦ κ. Γεωργίου Κοντοπούλου.

Abstract

A review of the contribution of the chaos theory to the knowledge on earthquake generation and earthquake prediction is attempted. It is shown that chaos theory: a) contributed to a better understanding of seismic faulting dynamics and of seismicity properties, b) explained difficulties in long term earthquake prediction and c) improved methods of intermediate term earthquake prediction. Chaos theory stimulated the introduction of different scientific hypotheses to Seismology, as well as new concepts, physical models, arithmetic simulation and analytical methods, which led to rationalization of several seismological observations that had puzzled seismologists for a long time. Thus, induced seismicity due to very low stress changes caused by human activity is well explained, now, by the assumption that parts of the earth's crust are at the verge of rupture, as it is suggested by the self-organized criticality hypothesis. Also accelerating seismicity preceding a mainshock is explained by the critical point hypothesis, which predicts such seismicity behavior if the mainshock is considered as a critical point. Furthermore, there is evidence that the chaos theory will probably contribute to a better understanding of problems related to short-term earthquake prediction.

1. Introduction

A scientific theory is useful for a specific scientific discipline if, both the study of a particular aspect of nature, as well as the prediction ability of the very scientific field that studies this aspect, are served. Chaos theory represents a new look at the study of non-linear dynamic systems. Physical

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* Β. Κ. ΠΑΠΑΖΑΧΟΣ, Συμβολὴ τῆς Θεωρίας τοῦ Χάους στὴν ἔρευνα γιὰ τὴν πρόγνωση τῶν σεισμῶν.

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processes in the earth's lithosphere compose a non-linear complex system and the generation of earthquakes is part of this process (Keilis-Borok et al., 2001). Thus, chaos theory suggests novel routes to understand seismological phenomena. On the other hand, since chaos is not totally random and is revealing patterns of order (Fisher, 1985), an insight into these patterns could have useful applications to earthquake prediction. Seismological research work has already been stimulated by this emerging discipline. During the last fifteen years several new concepts (power-laws, fractals, scale invariance, self-similarity), physical models (slider-block, sand-pile, forest-fire, site percolation), numerical simulation and analytical methods (cellular automata models, renormalization group theory, hierarchical models) and scientific hypotheses (deterministic chaos, self-organized criticality, critical point) have been introduced into Seismology.

A power law is a relation in which a physical quantity is linearly related to another quantity raised to some power, that is, the logarithm of one quantity is linear function of the logarithm of the other quantity. Thus, the frequency of seismic faults in a broad region is related to the corresponding size of the fault by a power law, that is, the larger the fault the less the frequency of its appearance. **Fractals** are objects of which the frequency (number) is related to their size by a power-law. The power value in the fractal relation is the **fractal dimension**. The power-law distribution is the only one that does not include a characteristic length scale. Therefore, fractals are **scale invariant**, that is, they appear identical at a variety of scales. Also fractals have a **self-similar** stochastic distribution, that is, they behave in a similar form, independently from the range of sizes considered. The philosophy of fractals has been set forth by their inventor Benoit Mandelbrot (1967, 1982). Though crustal deformation may appear to be complex, it does obey fractal statistics in a variety of ways. Thus, seismicity of a region can be reliably quantified if we assume that its distribution is fractal (Kagan, 1997).

A simple model that includes properties of real faults, such as the stick-slip behavior and the elastic rebound, is the **slider-block model** (Burridge and Knopoff, 1967). It is consisted of blocks, which are coupled both to each other, as well as to a constant low velocity driver and are dragged along a surface. Friction between the surface and blocks can result in a stick-slip behavior that is characteristic of faults. Any asymmetry in the model results in classic chaotic behavior, that is, in Feigenbaum period-doubling route to chaos, even when the model consists only of two blocks with different frictional forces (Huang and Turcotte, 1990). A model, which involves the use of many slider blocks and combines their analog features and the high-order aspects of cellular-automata, shows also chaotic behavior, even though the system is completely deterministic (Carlson and Langer, 1989).

The **sand-pile model** is the simplest physical model that is used in order to investigate complex high-order dynamic systems. It is consisted of a pile of sand on a circular table, where grains of sand are randomly dropped on the pile, until the slope reaches a critical angle of repose. This is the maximum slope that a granular material can maintain without the "sliding-down-the-slope-grains" effect. The sand pile never reaches the hypothetical global critical state. As the critical state is approached, sand grains trigger avalanches at various sizes. The global frequency-size distribution of these avalanches follows a power-law and their geometrical distribution is fractal. This model and its counterpart homogeneous cellular automaton have been used as the prototypes for the self-organized criticality (SOC) hypothesis (Bak et al., 1987, 1988). These models have also been in use to support the idea that regional (and global) seismicity can be explained by the assumption that the crust is in a SOC state at this scale (Bak and Tang, 1989).

In the basic **forest fire model**, trees are randomly planted on a grid and this is the steady input. Sparks are randomly dropped on the grid and if a spark lands on a tree then that tree and all adjacent trees are burnt. Properties of forest fire model are investigated by its counterpart cellular-automaton model. The random planting of trees corresponds to the lithospheric plate motion and the fires correspond to the earthquakes. The frequency-size distribution of fires is found to be fractal, that is, fires show a self-organized critical behavior. There are many variations of this basic forest-fire model according to the rules of the corresponding cellular-automata model (Bak et al., 1992; Turcotte, 1999).

The **site percolation** model describes the flow of a fluid through a porous medium. This model is proper for examining critical point problems, because the percolation probability is a tuning parameter and the critical point corresponds to the critical point percolation probability. The frequency-size distribution of percolation clusters follows a power-law scaling only in the immediate vicinity of the critical point and it is there where self-similarity occurs. For smaller values of probability the distribution of clusters is Poissonian and the frequency-size distribution of clusters is exponential (Stauffer and Aharony, 1992). This model is of interest to Seismology because mainshocks have been considered as critical points (Sornette and Sornette, 1990; Jaume and Sykes, 1999).

Dynamical complexity such as self-organized criticality (SOC) and critical point behavior can be simulated using highly simplified models of spatially extended dynamical systems, called **cellular-automata models**. A cellular-automaton consists of an array of cells, each of which is assigned a dynamical variable. The original example of such model, used by Bak, Tang and Wiesenfeld (1987, 1988) to simulate SOC, is composed of a square grid of boxes, while particles are randomly added to the boxes. When a box contains four particles, they are distributed to the four adjacent boxes and particles are lost in redistributions from edge and corner boxes. After the redistribution from a box, if any of the adjacent boxes has four or more particles, further redistributions are required. Although multiple events are common, the model involves only nearest neighbor interactions, while the computations are simple. In principle, they could study three-dimensional partial differential equations, yet the numerical calculations would be prohibitly time consuming. Bak and Tang (1989), based on this model, argued that regional seismicity is an example of self-organized criticality. However, this homogeneous model is oversimplified. Investigations of heterogeneous cellular-automata, which have different nearest neighbor laws or model geometry, produce different types of dynamical behavior (Steacy and McCloskey, 1999; Sammis and Smith, 1999; Weatherly et al., 2000).

Renormalization group theory is the transformation of a set of equations from one scale to another, by changing of variables. This procedure has successfully been used in treating a variety of phase change and critical point problems. By considering a relatively simple system at the smallest scale, the problem, then, is renormalized in order to utilize the same system at the next larger scale and the process is repeated at larger and larger scales. Thus, within the framework of the hypothesis that preshock accelerating seismicity approaches criticality and that the mainshock is a critical point, the renormalization group theory has been applied to deduce the failure process at a larger length scale and closer to the main failure time, using the failure process at a small spatial scale and temporally far from the global failure (Saleur et al., 1996). **Hierarchical methods** are similarly applied to extract the dominant structure at some scale, based on the knowledge of the structure at smaller scales. Thus, Ouillon et al. (1996) mapped joint and fault patterns at different scales (from 1cm to 100km) and applied such procedure to quantify the multiscale behavior of faulting anisotropy.

Self organized criticality (SOC) is the spontaneous organization of a system, driven slowly from outside, in a dynamical stationary state which is characterized by power-law spatial, temporal and size correlations (Bak et al., 1987, 1988). Such systems are dissipative (energy is released), spatially extended, have many degrees of freedom and exhibit long-range interactions. At this state, the system is marginally stable, that is, minute perturbations can make it unstable. The stationarity condition, however, ensures that the system is not in a transient phase, that is, when perturbed it comes back to its marginal stability. The critical state is an **attractor** of the dynamics. The self-organized criticality hypothesis is substantiated by various numerical and analytical studies (cellular automata, sand pile model, etc), as well as by observations. The earth's crust on a regional (or global) scale, or parts of it on a local scale, has been considered as being in a SOC state (Bak and Tang, 1989; Sornette, 1991). The driving forces in this case are caused by the really slow lithospheric plate motion (~cm/yr) in comparison with the slip motion on the crustal seismic faults (~m/sec). The SOC in the earth's crust is not a result of diffusion from a nucleus but the outcome of the repetitive action of rupture cascades. In other words, different portions of the crust become correlated at long distances by the action of the earthquakes, which transport the stress field fluctuations in the different parts of the crust many times back and forth, up to the point when the system is finally organized.

Critical point of a system is the point when properties of the system suddenly change. Points at which materials change phase are considered as critical points. Thus, the point at which liquid water changes to vapor due to an increased temperature (tuning state variable) is a critical point. Also a magnet, heated to a certain temperature, abruptly loses its magnetism at the critical point. Just before the critical point, there is a period when the system is at a **metastable state** (superheated water prior to a steam explosion, etc). At this state, several power-law scales hold, that is, the system is in a self-organized criticality. A mainshock can be considered as a critical point (Sornette and Sornette, 1990). The state variable for earthquake generation is the stress and the period of metastable state is the time when the values of stress vary between the dynamic friction stress and the static friction stress (Rundle et al., 2000). During this period, the Benioff strain (square root of energy) of the intermediate magnitude preshocks is accelerating with the time to the mainshock by a power-law. Similarly, the stress correlation length is accelerated according to a power of the time to the mainshock.

The purpose of the present paper is to show how these new ideas contribute to a better understanding of the earthquake generation process and, consequently, how to handle effectively problems related to earthquake prediction. It consists of three main parts. In the first part, basic information is given on earthquake generation. In the second part, the main contribution of the chaos theory to seismological knowledge is presented. In the third part, the problem of earthquake prediction is discussed in the light of the new ideas stemming from the chaos theory.

2. Earthquake Generation Process

Earthquake generation has puzzled philosophers and scientists since antiquity. Ancient Greek physical philosophers were the first who attributed earthquakes to physical causes. Thales from Miletos (624-546BC) believed that the water is responsible for earthquake generation, Pythagoras (570-496BC) attributed earthquakes to the heat which originates from the earth's interior and Archelaos (5th century BC) thought that air (or vapour) causes earthquakes. The thoughts of Archelaos have been further developed by Aristotle (384-323 BC) and his ideas were dominant for about two thousands years, that is, up to the sixteenth century when Agricola (1494-1555) and Garden (1501-1576) attributed earthquakes to chemical reactions.

Surface fault traces observed in the epicentral area of some large earthquakes during the nineteenth century led Lyell and other geologists to associate earthquakes with faults. General acceptance of the modern idea that faulting causes earthquakes came gradually after the 1906 San Francisco big earthquake, when H.F.Reid (1910) interpreted the geodetic observations (triangulations) by his "elastic rebound theory". As to the causes of faults, it was at the end of 1960s, when the theory of "lithospheric plate tectonics" was proposed (McKenzie and Parker, 1967; Isacks and Oliver, 1968) and was later proved very efficient in explaining, among others, the driving mechanism which cause seismic slip on faults.

In the paragraphs that follow some basic information, related to the causes of earthquakes and to the properties of seismicity, is given.

2.1. Causes of earthquakes

According to the **elastic rebound theory**, the crustal rocks store potential energy during a slow and gradual strain accumulation. When the accompanying elastic stress accumulates beyond the competence of the rocks, there is a fracture on a preexisting **seismic fault** and the distorted blocks snap back toward equilibrium and cause slip on the fault that produce the earthquake.

The diagram of figure (1) illustrates the process. The thick straight line represents the strike (direction) of a vertical fault. In *A*, the crustal rocks are in unstrained condition immediately after the previous earthquake when all stored potential energy (deformation energy) was released. In *B*, strain and stress is accumulated, the region is distorted and the lines normal to the strike of the fault (fences, roads, etc) are deformed into an "S" shaped curves but there is not as yet fracture. In *C*, the fault slip occurs and the deformation energy (dynamic energy) is released. Part of this energy is transformed to seismic wave energy, which makes the earthquake. After the generation of the earthquake, in *D*, the crustal rocks are again in an unstrained condition and the lines normal to the fault strike are again parallel but there is an offset. Driving forces continue to act and the process is repeated in a cyclic way, according to this theory. The distortion of crustal rocks is spread over many kilometers and is relatively small so that it can be measured only with precise instrumentation. For large earthquakes (e.g. M=7.5) the fault slip is of the order of a few meters (~3m), and the duration of the rupture is of the order of seconds (~20sec). The stresses build up by what we now recognize as plate motion, which is relatively slow (~10cm/yr).

Reid (1910) interpreted geodetic data collected before and after the 1906

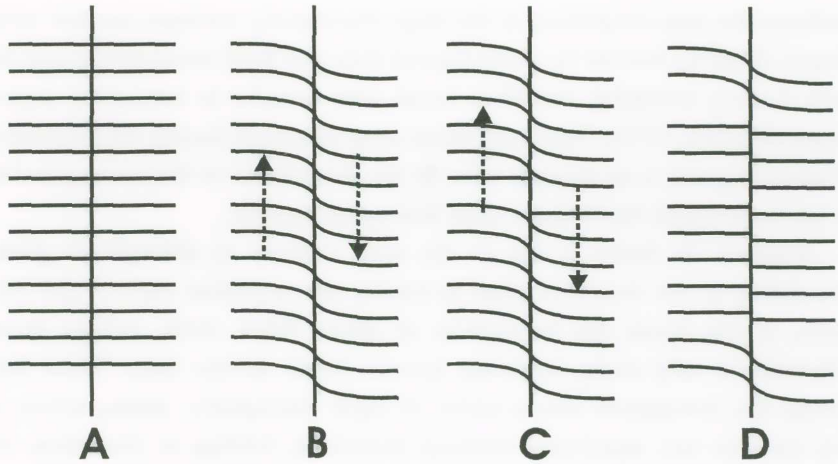

Fig.1. Schematic representation of the elastic rebound theory after Reid. The shape of the lines parallel to the strike of the fault are shown in A: immediately after the previous earthquake, B: just before the earthquake, C: during the earthquake, D: immediately after the earthquake.

earthquake and proposed that the next 1906-type earthquake in the San Francisco Bay area along the San Andreas fault would recur about the time that stress was restored to the level just before the 1906 shock. He proposed making geodetic measurements of deformation to ascertain that approximate time, i.e., to make long-term prediction. Although his elastic rebound theory, as subsequently interpreted in the plate tectonic framework, is the basis of much of Seismology including the seismic gap and seismic cycle hypotheses, recent research work shows that seismic faulting is a very complicated physical process. This view has a negative impact on earthquake prediction, as it is explained by the chaos theory, and will be discussed later. Faults almost never exist as single isolated structures. They occur within a population of faults and hence are not mechanically isolated. Thus, they may interact with other faults through their stress fields and, at a lower hierarchical level, an individual fault is segmented and its surface is inhomogeneous. Seismic rupture on a fault is a very complex phenomenon, as it comes out from geological observation (cross rocks of various strengths, bend, etc) and seismological observations (complex form of high-frequency waves in the near field, etc). An interesting evidence for this complexity is the large discrepancy between the low stress drop (~10MPa) derived by seismological data and field observations and the high stress (~100MPa) needed to break rock samples in laboratory experiments (Byerlee, 1978). Estimated stress drop in a fault during the generation of an earthquake is an average value of the stress drops in the heterogeneities of the fault which break easier than homogeneous rock.

Rupture on faults is due to the slow motions of **lithospheric plates**. According to the theory of plate tectonics, the outermost shell of the solid earth, which forms the lithosphere of about 80km thick, suffers strong deformation only along relatively narrow linear mobile belts. These belts divide the lithosphere into a series of rigid lithospheric plates, which do not undergo any significant internal stretching, folding or distortion. An important property of the lithosphere is that it transfers stresses at long distances. The lithospheric plates can move easily on the asthenosphere, which is formed of weak material.

2.2. Properties of seismicity

Seismicity shows significant variation in space, time and size. We present here some properties of seismicity, which are related to chaos theory and to earthquake prediction, such as some properties of regional seismicity, induced seismicity and accelerated seismicity.

It has been shown that seismicity in a relatively broad region (or globally) obeys the following Gutenberg and Richter (1954) law:

$$\log N = a\text{-}bM \qquad (1)$$

where N is the number of earthquakes with magnitudes M or larger and a, b are parameters determined by the available data for the region. Kagan (1997) analyzed regional and global earthquake catalogues and showed that the frequency-magnitude statistics follows the Gutenberg-Richter (G-R) relation (1) with a roughly universal b-value close to 1. Figure (2) shows the frequency-magnitude cumulative distribution for earthquakes, which occurred globally with $M \geq 7.5$ and for earthquakes which occurred in a very active region of western Greece (Ionian islands) with $M \geq 5.0$ for the period 1911-1989. The data for global seismicity are given by Pachecho and Sykes

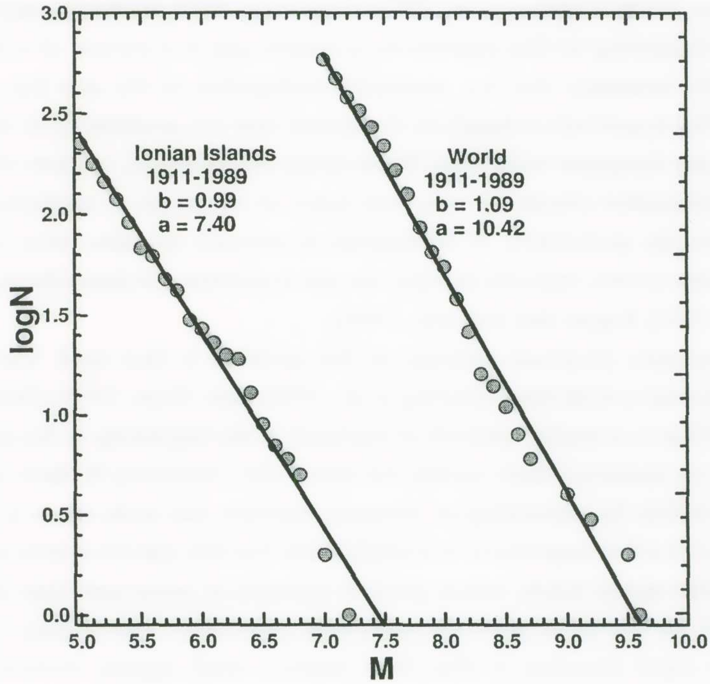

Fig. 2. Logarithm of the number, N, of earthquakes with magnitude M or larger for the time period 1911-1989 as a function of M for worldwide data (right) and for the region of Ionian Islands in Greece (left). It is observed that the slopes of the two lines (b-values) are both about equal to 1.

(1992) and for Ionian Islands are reported by Papazachos et al. (2000). It is observed that both the b-value globally and in the Ionian region is about equal to 1. The value of "a" of relation (1) is 10.42 for worldwide data and equal to 7.40 for Ionian Islands.

Earthquake statistics in a spatially limited zone seems to give results different from those obtained for regional or global seismicity and discussed above. Such zone can be a seismic fault or a simple plate boundary. This statistics led to the concept of **characteristic earthquake**, that is, the largest earthquake of the zone, which shows a quasi-periodic feature of occurrence (Schwartz and Coppersmith, 1984). The concept of the characteristic earthquake and cyclic occurrence is related to the **seismic gap** hypothesis

(Fedotov, 1968; Kelleher et al., 1973; Nishenko, 1991; Nishenko and Sykes, 1993). According to this hypothesis, a seismic gap is a section of a fault or of a plate boundary that has produced earthquakes in the past but is now quiet. This hypothesis is based on the notion that the probability of the next earthquake increases with time. Some scientists, however, support the idea that earthquakes cluster in time and space at all levels of magnitude and therefore, the probability of earthquake occurrence increases after another earthquake occurs, opposite to what the gap hypothesis predicts (Jackson and Kagan, 1993; Kagan and Jackson, 1995).

A recently proposed solution of this problem is that fault trace complexities evolve with time (Stirling et al., 1996; Ben-Zion, 1999; Shimazaki, 1999). That is, a fractal network of fractures at the beginning of the development of an immature fault system, for which the Gutenberg-Richter relation holds, evolves by smoothing or breaking barriers and ends up to a mature system with a few large faults or a single fault. For this mature system the **time predictable model** holds, which predicts increase of interevent time with increase of the slip in the previous mainshock (Shimazaki and Nakata, 1980).

The usual situation is that these relative small regions include a few interacting mainfaults and seismicity there obeys both the Gutenberg-Richter relation and the time predictable model. Thus, interevent time, T, in such a region depends both on the minimum magnitude, M_{min}, and on the magnitude, M_p, of the previous earthquake. Papazachos et al. (1997) used declustered data from 274 relatively small regions of the entire continental fracture system of the earth to derive the relation:

$$\log T = 0.19 M_{\min} + 0.33 M_p - 0.39 \log m_o + q \qquad (2)$$

where m_o is the annual seismic moment rate and q is constant. The repeat time given by (2) is of the order of decades. Therefore, the model expressed by this relation, in addition to its agreement with the G-R relation and the semi-periodic behavior of large earthquake occurrence, does not exclude time clustering of earthquakes of the order of some years.

Another important property of seismicity is that it can be induced by human activities. Induced seismicity has been mainly observed in cases of water impoundment in artificial lakes (Carder, 1945; Comninakis et al., 1968; Gupta and Rastog, 1976; Simpson, 1986), of fluid injection in the earth's crust under pressure greater than hydrostatic (Evans, 1966; Healy et al., 1968) and of hydrocarbon extraction from hydrocarbon fields (Grasso and Wittlinger, 1990; Guyoton et al., 1992). Induced seismicity by water impoundment or by fluid injection is attributed to stress variation due to pore pressure changes and are associated with normal faulting, while seismicity triggered by hydrocarbon extraction is attributed to stress changes caused by mass withdrawal and are associated with thrust faulting. Observations show that both pore pressure changes and mass transfers leading to incremental deviatoric stresses of smaller than 1MPa (10bar) are sufficient to trigger instabilities in the uppermost crust with magnitudes up to 7.0 and that once triggered, stress variations at least one order of magnitude less are enough to sustain seismic activity (Grasso and Sornette, 1998).

One of the most important cases of time variations of seismicity is the accelerating seismicity of intermediate magnitude earthquakes before the generation of a mainshock (Tocher, 1959; Mogi, 1969; Sykes and Jaume, 1990; Knopoff et al., 1996; Bowman et al., 1998; Papazachos and Papazachos, 2000, 2001). Bufe and Varnes (1993), based on a damage mechanics model, proposed the following power law relation to fit the time variation of the cumulative Benioff strain, S (cumulative square root of seismic energy):

$$S(t) = A + B(t_c - t)^m \tag{3}$$

where t_c is the origin time of the mainshock and A, B, *m* are parameters which can be calculated by the available data. Relation (3) is followed by the release of seismic energy due to frequency and magnitude increase of the intermediate magnitude preshocks as the generation of the mainshock is approached, while the frequency and magnitude of the small shocks remain constant in the preshock region. The region covered by the foci of intermediate magnitude earthquakes (preshock region) is an order of magnitude larger than the rupture (fault) region of the mainshock. The accelerating occurrence of intermediate magnitude earthquakes, expressed by relation (3), is of importance because it has been used for the development of a promising method for intermediate term earthquake prediction (Papazachos et al., 2002).

3. Contribution of Chaos Theory to the Rationalization of Seismological Observations

Seismological research on the physical process of earthquake generation in faults and on seismicity properties has benefited significantly by the chaos theory. In particular, deterministic chaos contributes to the better understanding of seismic slip properties on faults, self-organized criticality explains regional and induced seismicity and the critical point hypothesis interprets accelerated seismicity and its culmination by the generation of a mainshock. These three issues are discussed in the following.

3.1. Deterministic chaos in seismic faulting

Properties of seismic faults and earthquakes generated by fault slip have been widely explored by the deterministic laboratory and numerical slider-block model. This model has also been in use to study dynamic instabilities associated with complicated frictional laws (Burridge and Knopoff, 1967; Byerlee, 1978; Rice and Tse, 1986; Nassbaum and Ruina 1987; Huang and Turcotte, 1990; Narkouskaia and Turcotte 1992; Carlson and Langer, 1989; Beck, 2000).

The lowest order model that allows spatial variations consists of two sliding blocks coupled to each other and to the constant velocity driver by elastic springs (fig. 3). Huang and Turcotte (1990) used a simplified version of this model in which the masses of the two blocks are equal, the friction follows the simple static/dynamic friction law and the loading velocity of the driver is sufficiently low, so that the velocity during sliding can be assumed equal to zero. The system is completely deterministic because the differential equations of motions and their solutions are known. Based on these solutions they concluded that there is a cyclic behavior of the system when the frictional forces for the two blocks are equal (symmetric system), while for an asymmetric system the solutions exhibit deterministic chaos. This result was also reached by the use of the cellular automaton version of this two-block model (Narkounskaia and Turcotte, 1992). It has been further demonstrated that a one slider quasi-static model, with two state variable rate and state dependent friction, shows chaotic dynamics in the deterministic sense, that is, the existence of universal period which doubles in the stick-slip cycles en route to chaos (Becker, 2000). These results provide evidence that earthquake generation on seismic faults is an example of deterministic chaos.

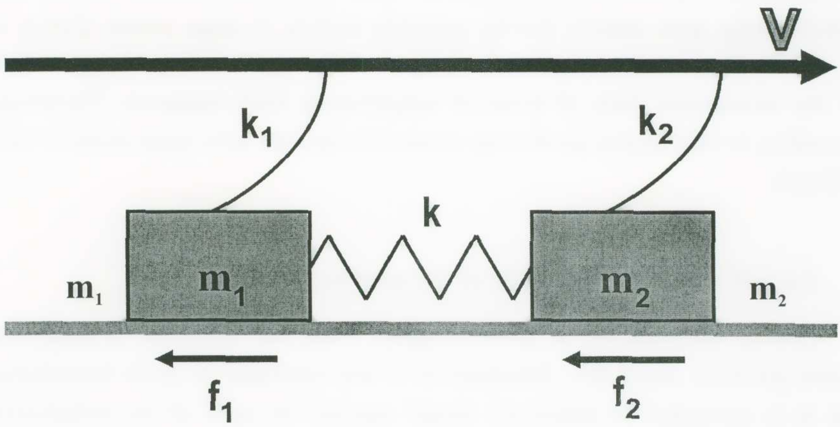

Fig.3. Illustration of the two slider-blocks model. m_1, m_2 are the masses of the two blocks, f_1, f_2 are the corresponding frictional forces, k, k_1, k_2 are the constants of the three springs and V is the constant velocity of the driver.

Linear arrays with number of slider blocks up to 400 and a velocity-weakening friction law have been considered to model a single fault (Carlson and Langer, 1989).

Although this system is completely deterministic, its behavior is chaotic, that is, two such identical systems, with nearly identical initial conditions and loaded at the same low rate, show exponential divergence in the slip difference as a function of time. Most of this difference occurs in large events, that is, large events cause most of the divergence between the two systems. Another important conclusion, which comes out from this model, is that the state of the system after a large event is very sensitive to the details of the initial conditions. Frequency-size statistics obtained for smaller events shows that these events obeyed a power law (fractal) relationship. The large events were associated with characteristic earthquakes on the fault, while the small events represent the background seismicity on the fault between characteristic earthquakes.

It can, then, be argued that most of the complexity of the earthquake generation process arises from the sensitivity of the stress distribution to the details of the slip distributions in large earthquakes, while chaos and non-linearity arise mainly during unstable sliding in large events (Sykes et al., 1999). Slight differences in the length of the rupture have a major effect on the subsequent state of stress of neighboring fault segments. Therefore, according to this model, predicting events beyond the next large event is very difficult.

3.2. Self organized criticality in the earth's crust

Crustal deformation is more complex than the idealized lithospheric model predicts, since this deformation is not confined in plate boundaries but it is extended in relatively broad regions. In spite of its complexity crustal deformation obeys some statistical order. Several authors made the hypothesis that the earth's crust is in a self-organized critical state and that earthquakes are self-organized critical phenomena. This hypothesis is based on simple mathematical modeling (Bak et al., 1987, 1988) and on comparison with seismological observations. Such observations are: a) the power law scaling expressed by the Gutenberg-Richter frequency-size distribution of earthquakes in regional seismicity, b) induced seismicity triggered by very small stress perturbations, c) the small rates of driving tectonic motion (~cm/yr) in comparison with the fault slip rate (~m/sec), d) the scale invariance of seismic fault populations over several orders of magnitudes, etc. (Grasso and Sornette, 1988). We present in the next paragraphs evidence for a rationalization of properties of regional and induced seismicity in the framework of self-organized criticality (SOC).

Figure (2) shows that regional seismicity and worldwide seismicity obeys the cumulative frequency-size relation (1) with a b-value about equal to 1. It has been shown that this relation is equivalent to fractal distribution (Aki, 1984; Turcotte, 1997).

The strain released during an earthquake is directly associated to seismic moment, M_o (in Joule), which is related to the moment magnitude, M, of the earthquake by the relation:

$$\log M_o = cM + d \tag{4}$$

where the constants have values c=1.5, d=9.1 (Hanks and Kanamori, 1979) and with the rupture (fault) area, S, by the relation:

$$\log M_o = \frac{3}{2}\log S + k \tag{5}$$

where k is constant (Kanamori and Anderson, 1975). From relations (1), (4), (5) we have:

$$\log N = -\frac{b}{c}\log M_o + A \tag{6}$$

$$\log N = -\frac{3b}{2c}\log S + B \tag{7}$$

where $A = a + \dfrac{bd}{c}$, $\quad B = a - \dfrac{b(k-d)}{c}$

Relations (6) and (7) lead to the conclusion that the cumulative frequency of earthquakes in a region follows power laws with the seismic moment (and with seismic energy), as well as with the rupture area (and with the fault length), which suggests that relation (1) is entirely equivalent to a fractal distribution.

The distribution of objects is fractal when the number N of objects with characteristic linear dimension greater than r is given by the relation:

$$N = C \cdot r^{-D} \tag{8}$$

where C, D are constants and D is called spatial fractal dimension (Grassenberg and Procaccia, 1983). If N is the cumulative number of earthquakes and $S \sim r^2$ from (7) and (8) we get:

$$D = \frac{3b}{c} \tag{9}$$

and taking the theoretical c=1.5 we receive:

$$D = 2b \tag{10}$$

which shows that the spatial fractal dimension, D, of the regional or worldwide seismicity is twice the b-value (Aki, 1984; Turcotte, 1997). For b=1, which is the usual value for b, we have D=2, that is, the spatial distribution of regional seismicity is two-dimensional as it is expected.

Accumulated observations on **induced seismicity** indicate that the hypothesis of self-organized criticality offers convincing interpretation for these observations (Grasso and Sornett, 1998). It interprets induced seismicity by reservoir impoundment or hydrocarbon withdrawal, because such human activity causes low stress changes (<1MPa), which can perturb preexisting state of stress and cause failure only in those parts of the crust, where these stresses are in fragile equilibrium with frictional strength, as predicted by the SOC hypothesis. The long-range spatial correlations of the stress field, predicted by the SOC hypothesis, explains the triggering of earthquakes with magnitudes up to 7.0 Richter by relatively low water depths in artificial lakes. The induced seismicity is also characterized by a power-law frequency distribution, similar to the Gutenberg-Richter relation, as expected for a region that is in a state of self-organized criticality.

Recent seismological observations and theoretical work show that the earth's crust is not everywhere and always at a SOC state, as the original oversimplified cellular automaton model indicated. Thus, there are numerous reservoir impoundments with water height larger than 100km, which have not triggered fast seismic activity (Gupta, 1985) and, therefore, where the crust is not at the verge of rupturing. That is, there are parts of the crust which are not in a state of self-organized criticality (Grasso and Sornette, 1998). This is supported by geological and seismological observations, which indicate that characteristic earthquakes in a fault show quasi-periodic behavior and do not follow any power law distribution. On the other hand, such quasi-periodic behavior of large events has been also deduced from recently proposed inhomogeneous cellular automata which better resemble nature (Sornette and Sammis, 1995; Sammis and Smith, 1999; Weatherly et al., 2000), from studies of avalanches in physical sand piles (Rosendahl et al., 1994) and from other theoretical work (Ben-Zion et al., 1999). If the earth's crust is at all times in a SOC state then this occurs in global or continental scale only (Sykes et al., 1999).

3.3. A mainshock as a critical point

Among the attempts to apply chaos theory for the understanding of earthquake generation is the modeling of earthquake process as a critical phenomenon, culminating in a large event (mainshock), which is analogous to a kind of critical point (Somette and Sornette, 1990). Critical point systems are closely related to self-organized critical systems. Rather than remaining perpetually near a critical state, critical point systems progressively approach and retreat from a critical state. The approach to criticality corresponds to the growth of long-range spatial correlations of a physical property of the system (e.g. stress). As long-range stress correlations formed in the earth crust, large events become progressively more likely to occur. The region reaches a critical state when stress correlation extends up to the size of the region. In the critical state, the generation of a large earthquake (mainshock) is possible. Cumulative energy release prior to the mainshock follows a power law time-to-failure relation. The mainshock results in the failure of a considerable portion of the region, destroying long-range stress correlations and criticality on its network and returning the system far-from failure (Sornette and Sammis, 1995; Saleur et al., 1996). A period of relative quiescence follows, after which the process is repeated by rebuilding correlation lengths toward criticality and the next mainshock.

Validation of the critical point model can have important theoretical and practical consequences. Thus, if this model represents the physical process that leads to the generation of a mainshock, the crust cannot be in a continuous state of self-organized criticality in a region, since the mainshock reduces the stress below the SOC state and remains so for a long period of time. As stress is slowly re-established by tectonic loading, a region approaches a SOC state during the last part of the cycle prior to the next mainshock. The presence of that state can be regarded as an intermediate term precursor rather than as an impediment to prediction because seismicity in the critical (preshock) region has certain observable premonitory peculiarities that can be used in order to estimate the parameters of the oncoming mainshock (Papazachos and Papazachos, 2000). Recent strong evidence, which support the critical point model for earthquake generation, has been deduced from laboratory experiments, seismological observations and statistical physics.

Laboratory experiments show that rupture process in heterogeneous media is a critical phenomenon. A power law increase in the cumulative seismic strain is expected in such process and relation (3) is applied (Sornette and Sammis, 1995; Andersen et al., 1997). This relation has been proved to fit well cumulative accelerating Benioff strain in preshock (critical) regions before and up to the generation of a mainshock in several seismotectonic regimes (Bowman et al., 1988; Papazachos and Papazachos, 2001). On the other hand, the critical point dynamics predict a growing spatial correlation length, L, according to a power law relation of the form:

$$L(t) = Z(t_c-t)^k \tag{11}$$

where Z is positive and k negative. This relation has been successfully applied to data of preshock seismic activity in Southern California (Zoller and Hainzl, 2001) and shows that intermediate magnitude preshocks are associated with the growing correlation length of the regional stress field prior to a mainshock. The mainshock is viewed as being analogous to the critical point in a chemical or magnetic phase transition. Rundle et al. (2000) related the behavior of seismicity prior to a mainshock to the instability of superheated water (spinodal instability) prior to a steam explosion. They show that the power law activation associated with the spinodal instability is essentially identical to the power law increase in Benioff strain observed prior to a mainshock and found for the exponent a theoretical value of 0.25, which is in good agreement with the observed values of m in relation (3).

Recent work on inhomogeneous cellular automata models give further support to the idea that a mainshock can be considered as a critical point. In such models, where a specified fraction of the stress energy is lost from each step, energy release increases as a power-law of the time to the critical state; large events cluster in time and produce large stress perturbations that move the system out of the critical state. Such clusters are followed by a shadow period of quiescence and then a new approach back toward the critical state occurs (Sammis and Smith, 1999). If the stress in the rupture zone is not reduced to zero by a mainshock but it remains above a certain minimum stress level, then the rate of small earthquakes are unaffected by larger ruptures and change of occurrence rates is confined only to moderate and strong earthquakes in agreement with observations (Weatherlly et al., 2000). Such behavior can also explain the relatively low stress drop (~5Mpa) observed for mainshocks, because these shocks do not drain the region by all its stress.

Figure (4) shows an example of the Benioff strain released by shocks with M≥4.8 in the critical region of the 28 March 1970 mainshock in western Turkey before, during and after its generation. The accelerated energy release before the mainshock and the quiescence after the mainshock is obvious.

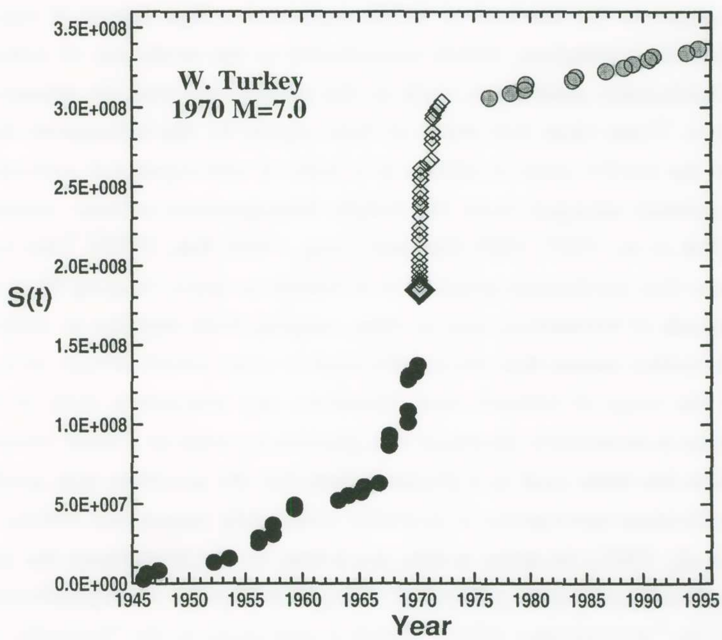

Fig.4. Time variation of the cumulative Benioff strain release by shocks with M≥4.8 in the critical region of the mainshock of 28 March 1970 (39.2°N, 29.5°E M=7.0) in western Turkey. Black circles, diamonds and shaded circles show strain energy released by preshocks, mainshock (including aftershocks) and postshocks, respectively. Accelerating seismic energy release during the preshock period and quiescence during the postshock period is observed.

4. Earthquake Prediction

Earthquake prediction has been the "dream" of scientists and other people for long time. This is due to the fact that it is widely believed that prediction will save lives and properties from earthquakes, which cause large number of fatalities in a short time and have a large psychological and economic impact on society. Up to the present, however, only statistical earthquake forecasting has been universally accepted, that is, estimation of the probability that earthquakes with a certain size will occur in a certain region over a specified time.

The development of the new global tectonics and of the theory of lithospheric plates in the last half of 1960s supported a high degree of regularity in earthquake generation, which contributed to the evolution of some ideas on the earthquake prediction, such as the seismic gap and the seismic cycle hypotheses. These ideas lost much of their repute by the subsequent hypothesis that the earth's crust is always at a state of self-organized criticality, as this hypothesis emerged from the simple homogeneous cellular automation model (Bak et al., 1987,1988; Bak and Tang, 1989; Bak, 1999). This hypothesis means that earthquake generation is fractal in space, ranging from meters to thousands of kilometers, and in time, ranging from minutes to millions of years. It further means that the earth's crust is everywhere, always and at any scale at the verge of rupture, and, therefore, any precursory state of a large earthquake is essentially identical to a precursory state of a small event. This hypothesis has been used as a physical basis for the assertion that prediction of an individual earthquake is probably inherently impossible (Main, 1997; Geller et al., 1997). In other words, according to this hypothesis the onset of the long-term generation process of a large earthquake is unpredictable because of the "microtremor effect" which is analogous to the "butterfly effect" in meteorology (Evison, 2001). This unpredictability, however, is caused by critical fluctuations rather than exponential sensitivity to initial conditions of a chaotic low-dimensional system (Bak and Tang, 1989).

The hypothesis that the earth's crust is at SOC state everywhere, always and at any scale, which is based on the oversimplified homogeneous cellular automaton model, is not correct (Grasso and Sornette, 1998; Sykes et al.,

1999) and, therefore, earthquakes must not be considered as inherently unpredictable phenomena. Instead, there is theoretical and observational information, within the framework of the chaos theory, which shows that there are precursory phenomena, which create new prospects for earthquake prediction. It must be emphasized that earthquake prediction must not be equated with short term earthquake prediction (uncertainties of the order of days to weeks in time) because intermediate term prediction (uncertainties of the order of months to a few years) or long term prediction (uncertainties of the order of years to decades) can have important positive social impacts. For this reason a very brief discussion for each of these three kinds of earthquake prediction follows.

4.1. Short-term prediction

Intensive research efforts have been made during the last four decades for short-term earthquake prediction. This research has focused on the identification of several kinds of precursory patterns (seismological, geophysical, geological, geochemical, geodetic, etc). Well known such precursors are foreshocks, seismicity quiescence, crustal strain changes, electromagnetic signals, temporal changes of seismic wave velocities, slip on geological faults, changes in groundwater geochemistry and in pore pressure of underground fluids (Wyss, 1997). Some hypotheses have also been made to link these precursors to a physical mechanism, such as the dilatancy hypothesis based on rock fracture laboratory experiments (Scholz et al., 1973). The practical results of this research work are rather poor. It is generally believed that short period deterministic prediction of an individual earthquake is not feasible, given the current status of scientific knowledge.

The failure to make any serious progress in short term earthquake prediction, after so hard efforts, can be attributed to the fact that several phenomena originally considered as precursory ones are not because their physical relation with the subsequent earthquake is debatable. The adoption of a new broader paradigm is probably needed to face this difficult and very important problem and such paradigm can emerge from the chaos theory. Thus, Bernard (1999, 2001) has proposed a broader conceptual framework of a generalized self-organized criticality model for the earth's crust, in which the large family of crustal transients will be researched.

4.2. Intermediate-term prediction

Efforts on intermediate-term earthquake prediction during the last decade have been mainly focused on the observed precursory accelerated seismicity, which has found a theoretical support by the critical point model. Thus, a method for intermediate term earthquake prediction has been developed during this decade on the basis of observational and theoretical findings.

Buffe and Varnes (1993) proposed the so-called time-to-failure analysis to model accelerated generation of intermediate magnitude earthquakes that preceded mainshocks in the Great San Francisco Bay Region. They proposed a procedure for earthquake prediction by application of relation (3), which has been tried in some cases. Bowman et al. (1998) proposed an algorithm to identify circular critical regions where accelerating Benioff strain occurred before large earthquakes along the San Andreas Fault system, by minimizing a curvature parameter C. This parameter is defined as the ratio of the root-mean-square error of the power-law fit (relation 3) to the corresponding linear fit error.

Papazachos and Papazachos (2000,2001) developed further this procedure by determining elliptical critical (preshock) regions for mainshocks in the Aegean area and defining five empirical relations proposed as additional constraints to the critical earthquake model. Three of these constraints relate the magnitude, M, of the mainshock with: a) the area of the critical region, b) the parameter B of relation (3) and c) the average magnitude, M_{13}, of the three largest preshocks, respectively, and can be used to estimate the magnitude of oncoming mainshocks. The other two constraints relate the duration, t_p, of the preshock sequence with: a measure of the long term seismicity in the critical region and with the parameter A of relation (3). A quality factor, q, has also been defined in an attempt to simultaneously evaluate the compatibility of an identified critical region with: these five relations, relation (3) and the optimum value of the curvature parameter. The geographical point where this quality parameter has its optimum (maximum) value is considered as the epicenter of an oncoming mainshock. The origin time of an oncoming mainshock is estimated by relation (3) and by the time of a preshock excitation, which has been found to be related to the origin time (Papazachos et al., 2001). Thus, a method called "accelerated seismic deformation method" has been developed by which the epicenter coordinates, magnitude and origin time of an ensuing mainshock can be predicted. Application of this method for a retrospective prediction of eighteen recent strong (M≥6.4) mainshocks in the Aegean area has shown that the uncertainties of the prediction are up to 100Km for the epicenter, ±0.5 for the magnitude, and ±1.5 years for the origin time with a confidence ~90% (Papazachos et al., 2001). Therefore, this is an intermediate term earthquake prediction method.

The method of "accelerated seismic deformation" has been applied to predict future mainshocks and successful such predictions have already been made. Thus, Karakaisis et al. (2002) identified by this method an elliptical critical region and predicted a strong mainshock in northern Aegean (the predicted parameters were 39.7° N, 23.7° E, M=6.0, t_c = 2001.1 yrs and the paper with these parameters was received by the Geophysical Journal International on 14 September 2000). Figure (5) shows a plot of the cumulative Benioff strain, S, as a function of time for the preshocks of the predicted earthquake. On July 26, 2001 a strong earthquake occurred in northern Aegean with parameters (39.1°N, 23.4°E, M=6.3, t_c = 2001.6) within the space, magnitude and time windows of the predicted earthquake. Therefore, it seems to be a promising method but further testing and scoring in future earthquakes is needed before it can be considered as a valid method for intermediate term earthquake prediction.

4.3. Long-term prediction

In long-term earthquake prediction we must distinguish between prediction of individual earthquakes and probabilistic forecasting of seismicity in a seismic zone.

The pattern of earthquakes along a fault resembles other chaotic phenomena and, for this reason, prediction of individual **earthquakes** is a very difficult problem. Even if we know the seismic fault where an earthquake is expected, it is difficult to predict the earthquake because its parameters (magnitude, origin time) are controlled strongly by the distribution of slip and

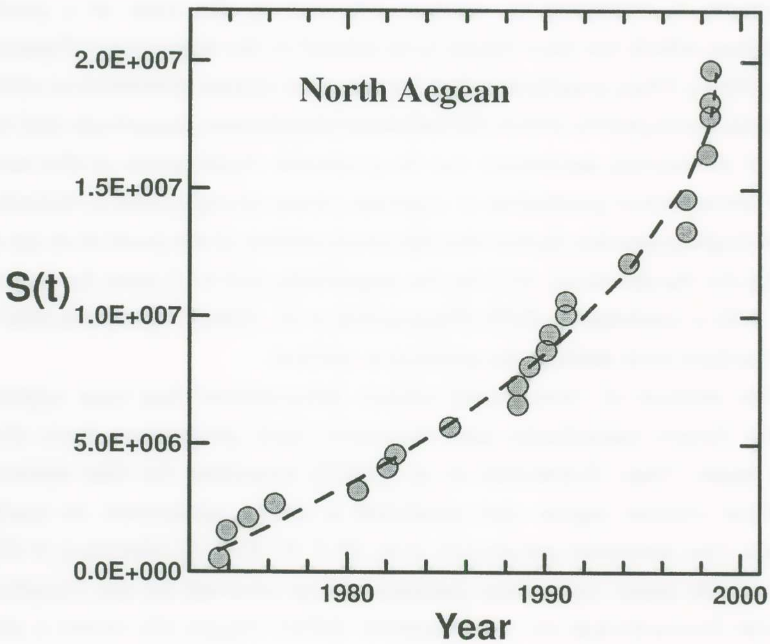

Fig.5. Accelerated Benioff strain (in Joule$^{1/2}$) released by intermediate magnitude preshocks in the critical region of the mainshock of 26 July 2001 near Skyros island (Karakaisis et al. 2002).

stress drop during the last strong earthquake. An additional argument, which has been used to support this idea, is based on the fact that application of the seismic gap hypothesis has not been successful. Therefore, better knowledge of the slip distribution in depth and along strike would have led to more accurate long-term predictions. Predicting more than one cycle ahead, however, appears to be inherently almost impossible, since considerable nonlinear behavior associated with a fault segment occurs at the time of large earthquakes (Sykes et al., 1999).

The mathematics of chaos is a step forward from randomness. Thus, while prediction of an individual earthquake is difficult, the bulk result on a seismic zone can be modeled quite precisely. In the case of the sand pile, it is the cone whose sides are at the angle of repose. In the case of earthquakes, it is an overall level of energy release that matches the long-term movements of the earth's crustal plates. This information gives the possibility to make a probabilistic forecasting of the seismicity in a zone and estimation of the seismic hazard at a site.

By the use of seismological, geophysical and geological data, a region is separated in seismic zones. By using historical and instrumental data the seismicity parameters for each zone (parameters of relation 1, maximum expected magnitude, etc) are calculated. Then, by assuming Poissonian (random) time distribution of earthquakes we can make probabilistic forecasting of seismicity in each zone. Then, by using estimated seismicity and attenuation of seismic wave relations we can make probabilistic assessment of the seismic hazard at any site (Cornell, 1968). The assessed hazard by this method is time independent because it is based on the assumption that seismicity in a zone is chaotic, that is, time independent. Relation (2) in combination with a normal distribution of the difference between observed and calculated interevent times can be used in order to estimate time dependent seismicity in a seismic zone (Papazachos et al., 1997) and assess time dependent hazard (Papaioannou and Papazachos, 2000). Therefore, probabilistic forecasting of seismicity can be confidently applied for long-term seismic hazard assessment. This is useful for planners, emergency agencies and designers of buildings and other technical structures.

5. Conclusions

The chaos theory has drastically affected seismological research on the physical process of earthquake generation and on earthquake prediction, by stimulating the introduction of several concepts, physical models, arithmetic simulation and analytical methods, as well as scientific hypothesis to Seismology.

Physical models, and particularly the slider-block model, indicate that rupture on a seismic fault has characteristics of deterministic chaos that prevail during the generation of large earthquakes on the fault.

Properties of regional and global seismicity are interpreted by the Self-Organized Criticality (SOC) scientific hypothesis. Induced seismicity indicates that parts of the Earth's crust are in a state of SOC at a local scale too, but not all crust is always and at all scales in a SOC state.

The scientific hypothesis that a mainshock can be considered as a critical point interprets satisfactorily preshock accelerating seismicity, the mainshock occurrence (including aftershocks) and postshock quiescence.

Statistical long-term time-independent forecasting of earthquakes in a seismic zone is an internationally accepted and practically applicable technique for seismic hazard assessment. Statistical long-term time-dependent forecasting is possible but it needs further testing. Long-term prediction of an individual mainshock (from years to decades) is very difficult because it needs very accurate information for the rupture properties of the previous mainshock, which occurred on the same fault.

Intermediate-term earthquake prediction (from months to years) is very probably possible but further testing and scoring is needed before it can be considered as a valid method.

Short-term earthquake prediction (from days to weeks) is not feasible with the present state of knowledge, although much effort has been made to this goal during the last three decades. New scientific paradigms should be formed and used for this purpose and the chaos theory shows routes to such ideas.

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ΠΕΡΙΛΗΨΗ

Ἡ συμβολὴ τῆς θεωρίας τοῦ χάους στὴν ἔρευνα γιὰ τὴν πρόγνωση τῶν σεισμῶν

Στὴν ἱστορία τῆς Σεισμολογίας ὑπῆρξαν διάφορες περίοδοι ποὺ ἀποτέλεσαν σταθμοὺς στὴν ἐξέλιξή της. Ἡ πρώτη τέτοια περίοδος ἦταν ὁ 6ος π.Χ. αἰώνας, ὅταν γιὰ πρώτη φορὰ ἀποδόθηκαν οἱ σεισμοὶ σὲ φυσικὰ αἴτια, ἐνῶ προηγούμενα οἱ ποιητὲς (Ὅμηρος, Ἡσίοδος) ἀπέδιδαν τοὺς σεισμοὺς σὲ θεϊκὲς δυνάμεις καὶ ἰδιαίτερα στὸν Ποσειδῶνα τὸν ὁποῖον χαρακτήριζαν γαιήοχο. Ἔτσι, ὁ Θαλῆς ἀπέδιδε τοὺς σεισμοὺς στὸ νερὸ καὶ ὁ Πυθαγόρας στὴ ροὴ τῆς θερμότητας ἀπὸ τὸ ἐσωτερικὸ τῆς Γῆς. Ἄλλοι σταθμοὶ στὴν ἐξέλιξη τῆς Σεισμολογίας ἦταν: ἡ ἀνακάλυψη κατὰ τὸν 19ο αἰώνα ὅτι οἱ σεισμικὲς κινήσεις ὀφείλονται σὲ ἐλαστικὰ κύματα, ἡ γενικὴ παραδοχὴ στὶς ἀρχὲς τοῦ 20οῦ αἰώνα ὅτι οἱ σεισμοὶ γεννῶνται σὲ σεισμικὰ ρήγματα καὶ ὅτι τὰ σεισμικὰ ρήγματα προκαλοῦνται ἀπὸ τὴν κίνηση τῶν λιθοσφαιρικῶν πλακῶν ποὺ ἐπιβεβαιώθηκε κατὰ τὶς τελευταῖες τέσσερες δεκαετίες. Ὑπάρχουν σήμερα σοβαρὲς ἐνδείξεις ὅτι ἄρχισε ἤδη μία νέα φάση γρήγορου ρυθμοῦ ἀνάπτυξης τῆς σεισμολογικῆς ἔρευνας ποὺ ὀφείλεται στὴν εἰσαγωγὴ σ' αὐτὴ νέων ἰδεῶν, φυσικῶν μοντέλων, ἀριθμητικῶν μεθόδων προσομοίωσης καὶ ἐπιστημονικῶν ὑποθέσεων ποὺ προέρχονται ἀπὸ τὴ θεωρία τοῦ χάους.

Οἱ προηγούμενες «ἐπιστημονικὲς ἐπαναστάσεις» εἶχαν ὡς συνέπεια τὴν κατανόηση σὲ σημαντικὸ βαθμὸ τῶν φυσικῶν διαδικασιῶν γένεσης καὶ διάδοσης τῶν σεισμικῶν κυμάτων ἀλλὰ συνέβαλαν ἐλάχιστα στὴν ἔρευνα γιὰ τὴν πρόγνωση τῶν σεισμῶν. Ἀντίθετα, ἡ θεωρία τοῦ χάους ἄρχισε ἤδη ὄχι μόνο νὰ συμβάλλει στὴ βαθύτερη κατανόηση τῶν διαδικασιῶν αὐτῶν ἀλλὰ καὶ νὰ δημιουργεῖ, γιὰ πρώτη φορὰ στὴν ἱστορία τῆς Σεισμολογίας, σαφεῖς προϋποθέσεις γιὰ τὴ μεσοπρόθεσμη πρόγνωση τῶν σεισμῶν (μὲ χρόνο πρόγνωσης ἀπὸ μῆνες μέχρι λίγα ἔτη).

Μία ἀπὸ τὶς βασικὲς ἰδέες τῆς θεωρίας τοῦ χάους εἶναι ἡ Αὐτὸ-Ὀργανωμένη Κρισιμότητα (ΑΟΚ), ποὺ σημαίνει ὅτι διάφορα συστήματα στὴ φύση καὶ στὴν κοινωνία αὐτο-ὀργανώνονται σὲ μία κρίσιμη κατάσταση ὅπου ἐπικρατοῦν εὐαίσθητες ἰσορροπίες. Γι' αὐτὸ δευτερεύοντες ἐξωτερικοὶ παράγοντες μπορεῖ νὰ ἐπηρεάσουν τὸ σύστημα στὸν ἴδιο βαθμὸ ποὺ τὸ ἐπηρεάζουν σημαντικοὶ παράγοντες. Ἔτσι, ὁ στερεὸς φλοιὸς τῆς Γῆς θεωρήθηκε ἀρχικὰ (στὸ τέλος τῆς δεκαετίας τοῦ 1980) ὅτι βρίσκεται πάντοτε καὶ παντοῦ σὲ τέτοια κατάσταση, ἀφοῦ δευτερεύοντες παράγοντες ὅπως εἶναι ἡ φόρτωση μὲ νερὸ τεχνητῶν λιμνῶν μποροῦν νὰ διαταράξουν τὴν εὐαίσθητη ἰσορροπία του καὶ νὰ προκαλέσουν σεισμοὺς μὲ

μεγέθη μέχρι 7 Ρίχτερ. Ἡ ἀντίληψη αὐτὴ ἀποτέλεσε τότε τὴ θεωρητικὴ βάση ὥστε ὁρισμένοι σεισμολόγοι νὰ ὑποστηρίξουν τὴν ἄποψη ὅτι οἱ σεισμοὶ εἶναι μὴ προβλέψιμα φαινόμενα, ἀφοῦ ὁποιοδήποτε πρόδρομο φαινόμενο ἔχει πιθανότητα νὰ ἀκολουθηθεῖ ἀπὸ πολὺ μικρὸ ἢ πολὺ μεγάλο σεισμό. Δηλαδή, ὅπως «μιὰ καταιγίδα στὴ Νέα Ὑόρκη μπορεῖ νὰ προκληθεῖ ἀπὸ τὸ πέταγμα μιᾶς πεταλούδας στὸ Πεκίνο», ἔτσι «ἕνας μεγάλος σεισμὸς στὴν Ἑλλάδα μπορεῖ νὰ προκληθεῖ ἀπὸ ἕνα μικροσεισμὸ στὴν Ἀγγλία».

Νεώτερες, ὅμως, θεωρητικές, ἐργαστηριακὲς καὶ παρατηρησιακὲς ἔρευνες, οἱ ὁποῖες ἔγιναν στὰ πλαίσια τῆς θεωρίας τοῦ χάους, κατέληξαν σὲ τρία σοβαρὰ συμπεράσματα. Τὸ πρῶτο εἶναι ὅτι οἱ μεγάλοι σεισμοὶ (κύριοι σεισμοὶ) δὲν ἀποτελοῦν μέρος τῆς διαδικασίας αὐτοοργάνωσης τοῦ φλοιοῦ ἀλλὰ εἶναι κρίσιμα σημεῖα ὅπου καταλήγει ἡ διαδικασία αὐτή, ἀντίστοιχα μὲ τὰ κρίσιμα σημεῖα ἄλλων κρίσιμων φαινομένων (κρίσιμη ἔκρηξη κατὰ τὴ μεταβολὴ νεροῦ σὲ ἀτμό, κρίσιμη θερμοκρασία ἀπομαγνήτισης σώματος, κ.λπ). Τὸ δεύτερο συμπέρασμα εἶναι ὅτι ἡ γένεση τοῦ κυρίου σεισμοῦ καταστρέφει τὴν Αὐτὸ-Ὀργανωμένη Κρισιμότητα καὶ συνεπῶς ὁ φλοιὸς τῆς Γῆς δὲ βρίσκεται πάντοτε σ' αὐτὴ τὴν κατάσταση. Τὸ τρίτο καὶ σημαντικότερο συμπέρασμα εἶναι ὅτι, ὅπως συμβαίνει καὶ μὲ ἄλλα «κρίσιμα σημεῖα», τοῦ κυρίου σεισμοῦ προηγοῦνται παρατηρήσιμα πρόδρομα φαινόμενα μὲ τὰ ὁποῖα μπορεῖ νὰ γίνει πρόγνωση τοῦ ἐπικέντρου, τοῦ μεγέθους καὶ τοῦ χρόνου γένεσης τοῦ κυρίου σεισμοῦ. Τέτοια φαινόμενα εἶναι ἡ αὔξηση τοῦ ρυθμοῦ γένεσης τῶν προσεισμῶν ἐνδιαμέσου μεγέθους, ἡ αὔξηση τοῦ χώρου συσχέτισης τῶν τεκτονικῶν τάσεων ὅσο πλησιάζει ὁ χρόνος γένεσης τοῦ κυρίου σεισμοῦ, κ.λπ.

Στὸ Ἐργαστήριο Γεωφυσικῆς τοῦ Α.Π.Θ, ἀναπτύχθηκε κατὰ τὰ τελευταῖα τρία χρόνια μέθοδος μεσοπρόθεσμης πρόγνωσης ποὺ βασίζεται στὴν παραπάνω ἀρχή. Ἡ μέθοδος, ἡ ὁποία ἔχει δημοσιευθεῖ σὲ μεγάλα διεθνῆ περιοδικά, βρίσκεται ὑπὸ στατιστικὸ ἔλεγχο γιὰ νὰ καθορισθεῖ τὸ ποσοστὸ ἐπιτυχίας της. Τὰ πρῶτα ἀποτελέσματα τῆς μεθόδου εἶναι ἐξαιρετικῶς ἐνθαρρυντικὰ ἀφοῦ ἔγιναν ἤδη ἐπιτυχεῖς καὶ ἔγκυρες προγνώσεις τόσο τοῦ σεισμοῦ τῆς Σκύρου (26 Ἰουλίου 2001) ὅσο καὶ τοῦ σεισμοῦ τῆς Καρπάθου (22 Ἰανουαρίου 2002). Ἡ ἐπιστημονικὴ αὐτὴ ἐξέλιξη, ἡ ὁποία ὀφείλεται σὲ ἰδέες ποὺ προῆλθαν ἀπὸ τὴ θεωρία τοῦ χάους, δημιουργεῖ νέες συνθῆκες γιὰ τὴν ἀντισεισμική μας προστασία, ἀφοῦ ἡ μεσοπρόθεσμη πρόγνωση ἑνὸς ἰσχυροῦ σεισμοῦ παρέχει τὴ δυνατότητα λήψης μέτρων ἑτοιμότητας σὲ συγκεκριμένη περιοχή, ὥστε οἱ κοινωνικὲς συνέπειες τοῦ ἐπερχόμενου σεισμοῦ νὰ περιοριστοῦν σημαντικά.