# New plates, rates and dates

*Jean-Bernard Minster*

In the late 1960s, McKenzie and Parker[1] and Morgan[2] advanced the theory of plate tectonics, which proposes that the Earth's surface is covered by a mosaic of large plates that behave rigidly over geological time and move relative to each other in response to convection currents in the Earth's mantle. This theory quickly gained acceptance, particularly amongst geophysicists, and in 1968 Le Pichon put together the first self-consistent model to describe the relative motions of the major plates[3]. Second-generation models soon followed[4,5], and third-generation models were published a decade later, in 1978[6,7]. DeMets *et al.*[8] have now produced a revised model of plate motions that is sure to become a new standard and will probably remain so for years to come. This fourth-generation model, labelled NUVEL-1, crowns nearly a decade of effort by R. Gordon, S. Stein and their students, with the aim of improving our knowledge of plate kinematics in various regions of the world. NUVEL-1 describes the 'instantaneous' relative motions — that is, averaged over the geologically brief interval of the past 3 million years — of 12 major plates, and remedies most of the problems identified over the years with earlier models.

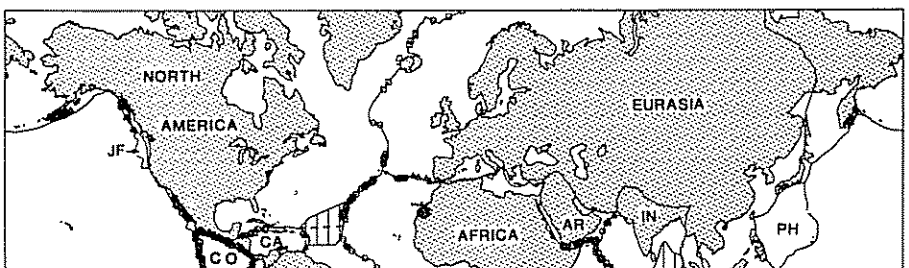
NUVEL-1 is derived from three basic data types: 277 spreading rates of new oceanic crust created at mid-ocean ridges (estimated from magnetic anomalies), 121 directions of relative plate motion (obtained from the azimuths of transform faults, which offset the ridge crest in many places) and 724 earthquake slip vectors: a total of 1,122 data points distributed along 22 of the 30 plate boundaries in the model. This represents more than a threefold increase in sampling over earlier data sets. (As in previous studies, data from continental plate boundaries are not used because of the geological complexities associated with deformation of the weak continental crust.) NUVEL-1 accommodates all the data extremely well, and is consistent with the hypothesis that major plates behave rigidly on a million-year timescale.

The differences between NUVEL-1 and previous models are significant. Whereas India and Australia have traditionally been assumed to belong to the same large plate, DeMets *et al.* use two plates, separated by an east–west equatorial zone of diffuse deformation (see figure). The NUVEL-1 relative plate velocities are generally slower, by about 10–15 per cent, than previous estimates. In particular, thorough reanalysis of the magnetic anomalies along the East Pacific Rise has led to spreading-rate estimates nearly 25 per cent slower than previous ones. This has important consequences. For example, consider the San Andreas fault in California: geological and geodetic observations show that it slips at a rate of 34 mm $yr^{-1}$ in central California, but the rigid-plate models in use until recently called for 58 mm $yr^{-1}$ of relative motion between the North American and Pacific plates. This so-called 'San Andreas discrepancy', which has puzzled geologists for nearly 20 years, is a considerably less severe problem with NUVEL-1, which predicts a plate slip rate of just 48 mm $yr^{-1}$. In particular, the apparent need for significant slip on faults other than the San Andreas along the central California margin[9] has been lessened substantially. The concomitant reduction in estimated seismic hazard, along a coastline that harbours such sensitive facilities as the Vandenberg Space Shuttle Launch Facility and the Diablo Canyon nuclear power plant, is of no small import.

By any measure, plate tectonics has been a tremendously successful theory, and almost all Earth scientists now depend on the availability of a reliable plate-motion model. For instance, geologists need such models to provide kinematic boundary conditions in studies of continental deformation zones such as Tibet or the Basin and Range. Geodynamicists use plate velocities as boundary conditions in calculations of mantle convection.

But the group who might benefit most directly in the short term from an improved plate-motion model may be the geodetic community. Space-geodetic techniques such as very-long-baseline interferometry and satellite laser ranging can be used to measure the distance between America and Europe to within 10 mm or so, variations in the length of day to 0.05 millisecond, and the direction of the wobbling axis of rotation of the Earth to 1 milliarcsecond (that is, the position of the pole to within 30 mm); but to do so, one must account for long-term tectonic motions[10]. Explicit corrections must be made for plate motions, and departures from the 3-million-year average motions show up in the data. One of the exciting achievements of the past decade is the demonstration that plate motions can be measured directly by space geodesy over intervals of a few years, and that these 'current' plate motions agree very well with geological ones. In fact, in a few cases such as the western United States where abundant data are available, the 5-year space-geodetic average is in better agreement with NUVEL-1 than with previous models.

Finally, on a tectonically active planet such as the Earth, where every point of the surface is in constant motion, the very choice of a convention to define a planetary coordinate system that is stable to the necessary degree of accuracy is not possible without selecting a certain plate-motion model. This plate model then becomes an intrinsic part of the definition of the planetary coordinate system. DeMets *et al.* have provided such a model, and since the enormous amount of work that they have done is unlikely to be repeated in the near future, NUVEL-1 is a good candidate for a plate-motion standard. □




Data locations and plate geometry for the NUVEL-1 model[8]. Regions marked with vertical lines indicate diffuse plate boundaries (between North and South America and between India and Australia). Abbreviations of plate names are: Cocos (CO), Caribbean (CA), India (IN), Arabia (AR), Philippine (PH) and Juan de Fuca (JF).

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NATURE VOL 346 19 JULY 1990

# NUVEL Cuisine: Platefuls of Data for Earth Scientists

A paper on plate tectonics has surfaced near the top of the current listing of the hottest papers in physics. Paper #2 presents a new global model which describes the motion of 12 major plates that slide ever so slowly around the Earth's surface. Dubbed "NUVEL-1," the model is based on measurements and readings culled from more than 1,100 locations along 22 of the 30 plate boundaries within the model. The numbers were averaged out for the last three million years—an interval easily qualifying as "current" in geological terms.

"This paper provides new information on the relative motion of the major plates," says Seth Stein of Northwestern University. "For example, it reveals which way the North American plate is going with respect to the Pacific plate, and how fast they're moving. If your interest is in, say, earthquakes, then you want to know that number. The motion of the earth's plates is really what drives all the geological processes that we see—earthquakes, volcanoes, mountain-building—you name it." Stein tells *Science Watch* that there is a surprisingly close correlation between estimates based on three-million-year averages and newer, real-time data from radio astronomy and satellite laser ranging. "This addresses one of the oldest questions in geology," he says. "How does what we see on a human time-scale compare to what geologists examine over tens of millions of years? The answer is that, to an amazing extent, they're the same" (see also R.G. Gordon and S. Stein in *Science*, 256[5055]:333-42, 17 April 1992).

Also new to the Top Ten are two related papers dealing with laser diode technology. Paper #4 reports on p-type doping in zinc-selenide semiconductors. "This was the highest conductivity in p-type zinc selenide ever reported," says Michael A. Haase of the 3M Company in St. Paul, Minnesota, "and it was sufficient for making things like laser diodes, which, as paper #5 reports, came along about a year later. The laser diode was the first ever made in this class of material, and the p-type doping was the fundamental building block that was required to make it. Before practical laser diodes can be made in this material, however, there are a couple of basic challenges remaining. One is making good, low-resistance contact to this new p-type zinc selenide—that is, figuring out how to put a metal on it and get electricity through it. The other challenge is improving the quality of these materials so that they work for a practical length of time."

A report on photoluminescence in porous silicon, by L.T. Canham, Royal Signals & Radar Establishment, Great Malvern, U.K., has now moved into the top spot. This paper entered the chart in sixth position only last period. "The enormous interest in this phenomenon," Canham has recently written, "is likely to result in further dramatic progress within the next year, both in our understanding of the physics and chemistry involved, and [in] potential exploitation.... There is a great deal of effort directed at fabrication of more ordered forms of luminescent porous Si. [Only] time will tell if silicon does indeed have an even brighter future" (see L. Canham in *Physics World*, 5[3]:41-4, March 1992).

NASA's Cosmic Background Explorer (COBE) has now flown onto the chart. Paper #7 is a preliminary report from 1990 on the cosmic microwave background spectrum. More detailed information from COBE, announced to the media last April, caused a sensation worldwide for what it seemed to reveal about the early universe (see also *Science Watch*, 3[5]:3-4, June/July 1992). Citations to this preliminary report came from more recent papers that discuss the new data.

Rounding out the rest of the Top Ten are reports on thermalization of photoexcited carriers in gallium-arsenide semiconductors (paper #8), on evidence for the 17 KeV neutrino (#9), and, in paper #10, on string theory and black holes by Edward Witten.

## WHAT'S HOT IN PHYSICS...

| Rank | Paper | Citations This Period (May-Jun 92) | Rank Last Period (Mar-Apr 92) |
|---|---|---|---|
| 1 | L.T. Canham, "Silicon quantum wire array fabrication by electrochemical and chemical dissolution of wafers," *Appl. Phys. Lett.*, 57(10):1046-8, 3 September 1990. [Royal Signals & Radar Estab., Great Malvern, U.K.] | 24 | 6 |
| 2 | C. DeMets, R.G. Gordon, D.F. Argus, S. Stein, "Current plate motions," *Geophys. J. Int.*, 101(2):425-78, May 1990. [Naval Research Lab., Washington, D.C.; Northwestern U., Evanston, Ill.] | 22 | * |
| 3 | M.R. Douglas, S.H. Shenker, "Strings in less than one dimension," *Nucl. Phys. B*, 335(3):635-54, 14 May 1990. [Rutgers State U., Piscataway, N.J.] | 19 | 7 |
| 4 | R.M. Park, M.B. Troffer, C.M. Rouleau, J.M. DePuydt, M.A. Haase, "p-type ZnSe by nitrogen atom beam doping during molecular-beam epitaxial growth," *Appl. Phys. Lett.*, 57(20):2127-9, 12 November 1990. [U. Florida, Gainesville; 3M Co., St. Paul, Minn.] | 18 | * |
| 5 | M.A. Haase, J. Qiu, J.M. DePuydt, H. Cheng, "Blue-green laser diodes," *Appl. Phys. Lett.*, 59(11):1272-4, 9 September 1991. [3M Co., St. Paul, Minn.] | 18 | * |
| 6 | D.S. Fisher, M.P.A. Fisher, D.A. Huse, "Thermal fluctuations, quenched disorder, phase transitions, and transport in type-II superconductors," *Phys. Rev. B—Condensed Matter*, 43(1):130-59, 1 January 1991. [Princeton U., N.J.; IBM Corp., Yorktown Heights, N.Y.; AT&T Bell Labs, Murray Hill, N.J.] | 15 | 2 |
| 7 | J.C. Mather, E.S. Cheng, R.E. Eplee, R.B. Isaacman, S.S. Meyer, R.A. Shafer, R. Weiss, E.L. Wright, C.L. Bennett, N.W. Boggess, E. Dwek, S. Gulkis, M.G. Hauser, M. Janssen, T. Kelsall, P.M. Lubin, S.H. Moseley, T.L. Murdock, R.F. Silverberg, G.F. Smoot, D.T. Wilkinson, "A preliminary measurement of the cosmic microwave background spectrum by the Cosmic Background Explorer (COBE) satellite," *Astrophys. J.*, 354(2):37-40, 10 May 1990. [NASA, Goddard Space Flight Ctr., Greenbelt, Md.; MIT, Cambridge, Mass.; U. Calif., Los Angeles; Caltech, JPL, Pasadena, Calif.; U. California, Santa Barbara; Gen. Sci. Corp., Landover, Md.; Princeton U., N.J.; Gen. Res. Corp., Danvers, Mass.; U. Calif., Lawrence Berkeley Lab., Berkeley, Calif.] | 13 | * |
| 8 | T. Elsaesser, J. Shah, L. Rota, P. Lugli, "Initial thermalization of photoexcited carriers in GaAs studied by femtosecond luminescence spectroscopy," *Phys. Rev. Lett.*, 66(13):1757-60, 1 April 1991. [AT&T Bell Labs, Holmdel, N.J.; U. Modena, Italy; U. Rome, Italy; Tech. U. Munich, Germany] | 13 | * |
| 9 | A. Hime, N.A. Jelley, "New evidence for the 17 KeV neutrino," *Phys. Lett. B*, 257(3-4):441-9, 28 March 1991. [Nucl. Phys. Lab., Oxford, U.K.] | 12 | * |
| 10 | E. Witten, "String theory and black holes," *Phys. Rev. D*, 44(2):314-24, 15 July 1991. [Inst. Adv. Study, Princeton, N.J.] | 12 | * |

SOURCE: ISI's Hot Papers Database

NB. Only papers published since May 1990 are tracked. An asterisk indicates that the paper was not ranked in the Top Ten during the last period. In the event that two or more papers collected the same number of citations in the most recent bimonthly period, total citations to date determine the rankings.

# A Better Fit for the Plate Tectonic Puzzle

*Reanalysis of geophysical data helps reconcile estimates of San Andreas fault motion and reduces the earthquake hazard*

For 15 years there was no agreement on how fast the plates are moving along one of the world's most studied plate boundaries, the one in California between the North American and Pacific plates that is called the San Andreas fault. But a recent reanalysis of evidence from the sea floor greatly reduces and possibly eliminates the discrepancy between direct, land-based measurements of recent plate motion and more indirect, marine measurements of motion during the past few million years. It also reduces estimates of the likelihood that offshore faults paralleling the San Andreas will rupture in damaging earthquakes.

The problem had been that the rate at which the opposing plates slip past each other on the San Andreas seemed to depend on how one measured fault motion. If a paleoseismologist measured the slippage during the great earthquakes of the past few hundred years or a geodesist measured the imperceptible straining of one plate edge against the other during the past decade, the recent rate appeared to be about 35 millimeters per year. But geophysicists, using evidence from the ocean crust to determine velocities and directions of motion of all the globe's plates during the past few million years, came up with relative motion between the Pacific and North American plates of 56 to 60 millimeters per year.

Taking account of the skewing effect of crustal extension centered on Nevada, the difference between the two types of measurements, known as the "San Andreas discrepancy," came to about 15 millimeters per year. Bernard Minster of Science Horizons in Encinitas, California, and Thomas Jordan of the Massachusetts Institute of Technology, whose 1978 model of global plate motions has been the standard of the field, attributed the discrepancy to a combination of crustal compression perpendicular to the San Andreas and strike-slip, San Andreas-like motion on faults paralleling the boundary to the west. They recently estimated the compression to be about 9 millimeters per year, which would account for the crumpling across the fault evident in such places as central California's Coast Ranges.

The site or sites of the missing strike-slip motion, amounting to 13 ± 5 millimeters per year, was not so clear, but Minster and Jordan suggested the San Gregorio–Hosgri fault system that runs just off the coast from south of San Francisco to Point Arguello north of Santa Barbara. If all the missing motion were to occur there during fault ruptures, enough large earthquakes would result to make that fault one of the most active in California. That would be all too active for coastal residents and the controversial Diablo Canyon nuclear power plant on the coast near San Luis Obispo.

R A Kerr

**A California crumple.** *The Coast Ranges are in part raised by plate motions that are not parallel to the San Andreas fault.*

Things may not be that bad after all. A group at Northwestern University now believes that its new model of global plate motions greatly reduces the San Andreas discrepancy and the consequent seismic hazard. Charles DeMets, Richard Gordon, Seth Stein, and Donald Argus have updated and reanalyzed the ocean crust data, such as plate spreading rates determined from magnetic lineations and plate directions derived from transform fault orientations. They found about the same amount of compression across the San Andreas as did Minster and Jordan, but only about 5 millimeters per year of strike-slip motion. That "implies that little strike-slip motion need be accommodated on faults west of the San Andreas . . . ," according to the group.

The protracted debate usually involved in a challenge to an entrenched model will not materialize in this case. The Northwestern model has two small but particularly significant changes that have convinced Minster and Jordan at least that it is the preferred model. One change is in the rate at which new ocean crust is forming in the Gulf of California. The Northwestern group analyzed seven magnetic profiles across the Gulf of California that reveal the rate of crustal formation recorded as new crust cools and locks in Earth's flip-flopping magnetic field. Their interpretation produces a spreading rate of 48 millimeters per year versus earlier interpretations of single profiles suggesting 58 or 65 millimeters per year.

In addition, the Northwestern group found an inaccuracy in the drafting of a figure in a 1971 paper used by Minster and Jordan to derive the rate of motion between the Pacific plate and the Cocos plate, the small, triangular plate tucked against Central America. The resulting 10% error, which was not in the original data, caused a 10% decrease in the relative motion of the Pacific and North American plates.

The San Andreas discrepancy is clearly smaller now, but it may still not be negligible, notes Jordan. "This obviously reduces the amount of strike-slip motion, roughly by a factor of 2," he says. "But there's still a potential [for significant seismic activity]. The uncertainties are large enough that the missing slip could be 0 or 10 millimeters per year. That's a big difference. I'd hate to see people become complacent and think we have no problem. We really need some firsthand, direct observations."

Useful direct observations are not that far off. Widely spaced geodetic measurements by the satellite laser ranging system that seemed to support a large discrepancy (*Science*, 10 January 1986, p. 116) are now consistent with a smaller difference. Anticipated measurements using the satellites of the global positioning system, says Jordan, should be accurate enough and closely spaced enough to resolve the question once and for all. ■ Richard A. Kerr

ADDITIONAL READING

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