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# Global Positioning System Network Monitors the Western Alps

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A high-precision GPS network was installed in the Western Alps in September 1993 to map the movement of the African and Eurasian plates in the Mediterranean region. The GPS measurements will explain how convergence is distributed in the Western Alps, the largest, highest, and most deformed range in the Alpine collision zone. If a large earthquake strikes the region, the network will also help constrain the dislocation at depth.

Measurements of convergence will be made every five years. Global plate motion models predict a north-south mean convergence rate of 6 mm/yr between the African and Eurasian plates in the Western Mediterranean region (Figure 1b). Most of this deformation is probably accommodated in the active mountain belts: the Pyrenees, Alps, Apennines, and Maghrebids. Deformation in these structures is complex. Compression and convergence occur in different directions, and active extension may be occurring in the Southern Apennines or Eastern Pyrenees. A regional GPS network within an interplate fiducial network is the best way to measure crustal deformation within mountain belts and place them in the tectonic framework of global plate motions.

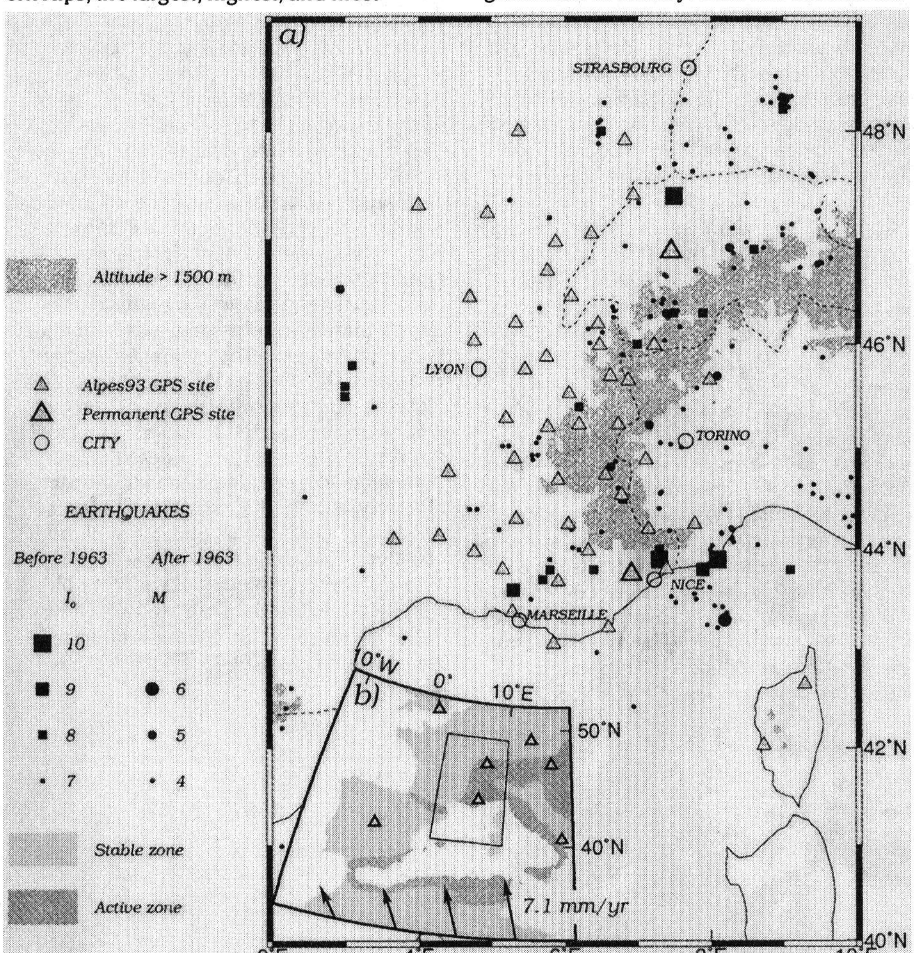


*Fig. 1. a) The area covered by the GPS network in the Western Alps. Earthquakes before 1963 are indicated by dark squares; earthquakes that struck after 1963 are depicted by dark circles. Triangles indicate GPS sites as detailed in the legend. b) The inset at the lower left of the figure shows the tectonic framework of the Western Mediterranean region. Black arrows indicate the motion of the African plate relative to the Eurasian plate (Courtesy of Charles DeMets). Original color image appears at the back of this volume.*

Our network, which consists of stainless steel pins set in bedrock, covers the internal and external range of the Alps with a typical spacing of 50 km (Figure 1a). This spacing increases in the peripheral zones to reach "stable zones" on the Eurasian plate and the Corso-Sarde microplate. Fifty-eight sites have been measured in France, Switzerland, and Italy by 37 dual-frequency receivers. Three sites were continuously tracked throughout the 15-day campaign called ALPES-93.

We combine the data from 50 of these sites with observations from the International GPS Service (IGS) in Europe to establish a robust reference frame, or vector coordinate system. Both station positions and satellite orbital parameters are estimated. Each daily session is first processed independently. This way, the data can be cleaned, breaks in coverage can be detected and repaired, and contaminated data can be eliminated, for example. The scatter in horizontal components of repeated estimates of relative position is better than 10 mm for 86% of baselines shorter than 550 km. One way to improve this solution is to compute more precise multiday orbital arcs by combining the independent daily solutions.

Future analyses will combine the daily solutions of the alpine network of 58 sites with the IGS network to estimate the coordinates of 66 stations and more precise multiday orbital arcs in a single global solution. Positions from September 1993 will be used as a reference.

## Data Archive and Distribution

All data related to the ALPES-93 campaign are accessible by Internet. Send requests for data to vigny@geophy.ens.fr. The archive includes raw data, RINEX data files, log sheets, and station descriptions, and precise orbits from all IGS centers for the corresponding period (1993 days 248–260, GPS week 712–714). Estimated station positions (~1 cm) and covariance matrices from our solutions are also available. There are also plans to produce a CD-ROM containing the data for use by the geodetic community.

*Acknowledgments:* We thank the French geophysical and geological laboratories of Chambéry, Grenoble, Montpellier, Nice, Paris, and Toulouse; l'Institut Geographique National in Paris; and Swiss and Italian partners at ETH Zurich and ING Roma. We thank the French organizations Centre National de la Recherche Scientifique, Institut National des Sciences de l'Univers, Electricite De France, and Centre National d'Etudes Spatiales for material and financial support.

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# New Mechanism Proposed for Glacial Cycles

PAGES 489–490

Were the ice ages triggered by an influx of extraterrestrial dust or meteoroids hitting Earth's upper atmosphere? A controversial and still unproven new theory recently described by *Muller and MacDonald* [1995] in *Nature* links the 100,000 year glacial cycle with changes in Earth's orbital inclination relative to the plane of the solar system. And, say the theory developers, the only logical mechanism they can find for the connection is increasing amounts of extraterrestrial material entering the atmosphere whenever Earth's orbit sweeps through the solar plane. Climate researchers are just beginning to test the model's predictions.

The orbital inclination hypothesis challenges the widely accepted Milankovitch theory, which attributes the glacial cycles to variations in solar heating (insolation) brought about by changes in the eccentricity of Earth's elliptical orbit. However, according to Richard Muller of the University of California at Berkeley and Gordon MacDonald of the University of California at San Diego, authors of the alternative orbital inclination theory, the changes in insolation predicted by the Milankovitch theory are too small to drive the glacial cycles. In addition, they cite discrepancies between the climatic changes recorded in sediments as $\delta^{18}O$ and the temperature variations predicted by variations in orbital eccentricity.

Muller says that their new theory came as a surprise. In an attempt to find an alternative to the Milankovitch mechanism, Muller and MacDonald mapped out the variations in the tilt of Earth's orbital plane measured relative to the invariable plane of the solar system—a plane that passes approximately through the orbit of Jupiter. "When it turned out to be [a cycle of] 100,000 years, I was shocked," says Muller.

Muller and MacDonald also analyzed 600,000 years of $\delta^{18}O$ sediment data from such sources as SPECMAP, a compilation of five seafloor cores. In their analysis the changes in orbital inclination are closely matched by changes in $\delta^{18}O$ values, which lag by 33 kyr.

Following the lead of other climate researchers, they also plotted their results as a frequency spectrum (time series transformed to frequency domain) to simplify the analysis of the complex data. These results are not yet published, but researchers say that their analysis shows the 100-kyr cycle is a single narrow peak, consistent with an astronomical origin of the cycle and inconsistent with a cycle attributed to eccentricity. Earlier spectral studies missed this inconsistency, Muller says, because they lacked sufficient resolution. If the connection between orbital inclination and glaciation is so strong, why has this 100-kyr cycle been missed by other researchers? According to Muller and MacDonald, if the wrong reference frame is chosen, the orbital inclination cycle is buried under a 70,000 year cycle of orbital plane precession. They claim that evidence of this 70,000 year cycle has been found in some sedimentary samples.

Other researchers have noted problems with the basic Milankovitch model, but argue instead that Earth's internal dynamics, such as the lag time to buildup continental ice sheets or changes in atmospheric carbon dioxide levels, also drive the climate cycles. In this model, Milankovitch plays a pacemaker role, while internal factors, which oscillate over time, also affect the system. These internal factors arise from complex, nonlinear mechanisms involving the oceans, air, land, and even possibly the biosphere. The result of this complex Milankovitch model, say these researchers, is a better fit to the observed climate data which is far more variable than a 100-kyr cycle.

However, Muller and MacDonald have also investigated the complicated Milankovitch models, and they find that the nonlinear coupling models, as well as other complex models, yield a frequency spectrum which they say is incompatible with the data. Those results have been submitted for publication.

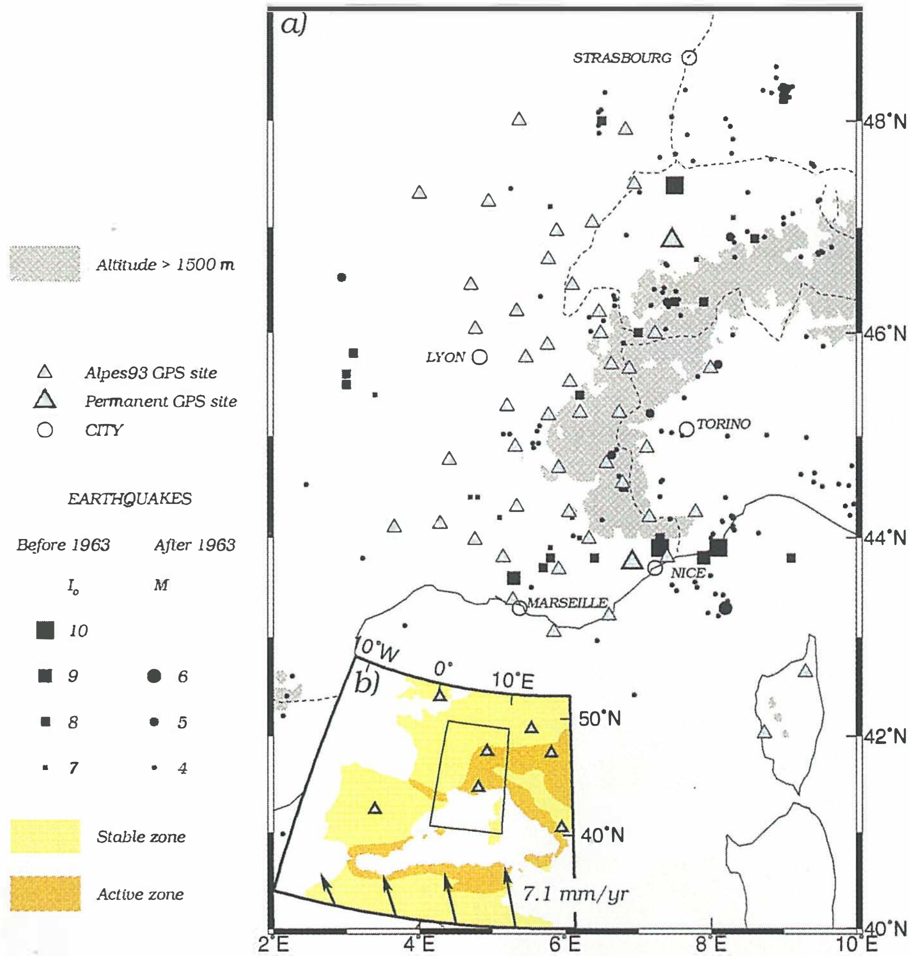
"Muller's and MacDonald's theory is an interesting one," says Wallace Broecker of the Lamont-Doherty Earth Observatory. However, he adds, "I really think that the evidence shows that the ice ages has been paced by the Milankovitch theory; more and more data [are] coming in that supports Milankovitch."

David Thomson of Bell Laboratories also expressed reservations about the new model, criticizing it for relying on a relatively short timescale of data. Thomson has also recently analyzed the sediment data, but out to 3.3 million years. He says that his longer timescale analysis is in "reasonable but not complete agreement" with the Milankovitch model. MacDonald, on the other hand, says that he and Muller, in unpublished results, have also analyzed time spans out to 3 Ma which support their conclusions, although they note that the 100-kyr glacial cycle is virtually absent outside the 0–1 Ma range. They add that many of the longer timescales are suspect, since they are "tuned" to match a Milankovitch model that contained a 100-kyr cycle based on eccentricity.

"It is likely that there are problems with the simple Milankovitch theory, but dust accretion [as an alternative mechanism] seems far fetched," says Thomson. Muller and MacDonald acknowledge that the extraterrestrial matter mechanism is the weak link in their theory, but point out that astronomers are still discovering lanes of interplanetary dust. For example, the Galileo probe to Jupiter recently encountered an unexpected cloud of dust.

MacDonald estimates that a tenfold increase in the influx of extraterrestrial matter could cause sufficient cooling to trigger the glacial cycles. "Dust would have a variety of impacts," says MacDonald. It could cool the Earth by an increase in the planet's albedo, deplete water vapor in the upper atmosphere which traps heat, or act as nuclei for the formation of high-altitude clouds.

Fortunately, the new model can be tested. A jump in the influx of extraterrestrial dust would lead to an increase in $^{3}He$, from mi-

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