

Earth science

Strength of the San Andreas

Mark D. Zoback

Knowledge of the rates of motion and the long-term record of earthquakes along the San Andreas fault system in California has improved markedly over the past 25 years. Such knowledge has made possible long-term estimates of earthquake probability, typically for periods of 30 years¹. But our understanding of the physics of faulting remains woefully inadequate — questions regarding the feasibility of shorter-term predictions, and whether the occurrence of one earthquake increases the probability of an earthquake on another fault, remain unanswered.

Hence the interest in a provocative paper by Christopher Scholz, published in *Geology*². Scholz argues that the San Andreas fault (Fig. 1) is relatively 'strong'. Over the past three decades, hundreds of laboratory experiments have indicated remarkably similar friction coefficients of between 0.6 and 1.0 for a wide range of rocks³. Extrapolating these observations to natural faults implies that extremely high stresses should be required to cause fault motion at great depth, assuming normal (approximately hydrostatic) pore pressures. Pore pressure is the pressure of fluids, principally water, within the cracks and pores of a rock at depth. In the context of Scholz's argument, a strong San Andreas means that, to a depth of about 10–15 km (where large earthquakes nucleate), the frictional resistance to sliding along the fault is high. This is essentially consistent with the stresses predicted from laboratory friction experiments with hydrostatic pore pressures.

There seems little doubt that laboratory friction data are applicable to the faulted crust within Earth's relatively rigid lithospheric plates. Data from deep boreholes around the world show high levels of shear stress at depth, consistent with the laboratory friction experiments⁴. Scholz argues that the San Andreas (and by inference the other major faults which bound lithospheric plates) has essentially the same frictional strength as the faulted crust within the plates — in other words, that the hundreds of kilometres of offset that have occurred along the fault have been accomplished without significant weakening of the fault with respect to the surrounding brittle crust.

In the 1960s, stick-slip sliding was discovered in the laboratory as a possible analogue for crustal faulting⁵. Stick-slip is the process by which a fault in a rock being deformed at a steady rate in the laboratory would 'stick', allowing stress to build over time, and then suddenly 'slip' like an earthquake, releasing part of the accumulated

stress. Thus, the stick-slip phenomenon, along with the uniformity of laboratory friction coefficients, seemed to point directly to the applicability of laboratory friction experiments to earthquakes on major faults such as the San Andreas.

However, by the late 1960s it became clear from conductive heat-flow measurements in boreholes near the San Andreas that this rapid frictional shearing was not generating any significant heat^{6,7}. Plate tectonics had revealed that the San Andreas has slipped hundreds of kilometres at long-term average rates of several centimetres per year. If the San Andreas had the frictional strength predicted by the laboratory data (friction coefficients of 0.6–1.0), appreciable frictional heat would be generated by the long-term motion of the fault.

The lack of observable frictional heat implied that the average fault strength is a factor of approximately 5–10 lower than that implied by laboratory friction coefficients^{6,7}. Markedly lower fault strength could mean several things: that processes may be occurring during faulting that are not seen in laboratory experiments; that the rocks within the San Andreas are very different in composition to those typically found in exposed fault zones; or that fault slip is aided by fluids trapped within the fault zone at abnormally high pressure. One critical, but questionable, part of Scholz's argument is to discount the significance of the heat-flow measurements near the fault, even though these data show no evidence of frictionally generated heat or appreciable convective heat transport⁷.

A further factor to be taken into account is the discovery in the late 1980s that the direction of the maximum horizontal principal stress near the San Andreas is, in general, nearly perpendicular to the fault. This indicated that frictional sliding is occurring at levels of shear stress that are much lower than those existing in the immediately adjacent crust^{8,9}. Taken together, the heat flow and *in situ* stress orientation data indicated to many researchers that the San Andreas, and perhaps other plate-boundary faults, was a profoundly weak fault in an otherwise strong crust.

By assuming fault-normal compression at large distances from the San Andreas and stress-free slip on the fault at depths below the earthquake-generating zone, Scholz presents a model in which the direction of maximum stress in the upper crust rotates near the fault to a direction about 45° from the fault trend. Although one study suggests that such a crustal stress pattern may exist in the 'big bend' area of the San Andreas¹⁰ (Fig. 1), such stress rotations can be ruled out in the vicinity of the Loma Prieta¹¹ and Morgan Hill¹² earthquakes, as well as on the San Francisco peninsula¹³, where fault-normal compression is observed within 1–2 km of the fault trace. Thus, the stress rotation Scholz is modelling appears not to be a general characteristic of the San Andreas.

What makes the issue of fault strength even more controversial is that some researchers have argued, on the basis of geodynamical modelling, that Earth's brittle crust is generally weak, implying that both intraplate crust and plate-bounding faults such as the San Andreas have low strength¹⁴. So different groups of investigators now view plate-bounding faults such as the San Andreas as weak faults in a strong crust^{6–9}, weak faults in a weak crust¹⁴, or strong faults in a similarly strong crust².



Figure 1 The San Andreas fault. The fault marks the divide between the Pacific and North American tectonic plates, and accommodates about 35 mm of the annual 48 mm of relative motion between them. The northern and southern segments last broke in major earthquakes in 1906 (magnitude 7.8) and 1857 (magnitude 8.2), respectively; the central section creeps steadily and does not accumulate strain. The other places marked are cited in the text. The physics of faulting is poorly understood, and the question of whether the San Andreas is a weak fault in a strong crust, or a strong fault in a strong crust (as Scholz² proposes), remains controversial. (Courtesy of the US Geological Survey.)

So where does this leave us? The stress measurements from deep boreholes appear to rule out the second, weak-fault/weak-crust, hypothesis, at least for rigid plate interiors. Nonetheless, we still find ourselves faced with contradictory theories and data, and remain largely in the dark about the physics of faulting along the San Andreas and similar plate-bounding faults. The absolute strength of the San Andreas is likely to remain controversial until we obtain measurements, from within the fault itself, of the stress levels and physical conditions under which earthquakes occur. ■

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translation of RNA into protein. The nuclear sequences were from a variety of species, and included newly determined sequences from red algae and protists (single-celled eukaryotes). The results strongly support the idea that green and red algae are ‘sister groups’, or closest relatives. Second, Moreira *et al.* analysed the gene encoding subunit RBP1 of RNA polymerase. Previous studies of this molecule resulted in a rejection of the possibility of a green algal/red algal clade⁵ (a clade is a group of species that share a common ancestor). But Moreira *et al.*’s analysis included more taxa and shows that this clade can no longer be rejected on such grounds. Third, analysis of a combined data set of 13 nuclear proteins provides strong support for the green algal/red algal clade. In addition, a six-gene analysis identified glaucophytes as the sister group of the green/red clade, but with only weak support.

These results are consistent with a single origin of all primary plastids; with Cavalier-Smith’s proposal⁷ of a ‘Kingdom Plantae’ composed of green algae, red algae and glaucophytes; and with evidence from the phylogeny of plastid genes⁸, and from the retention of a bacterial cell wall by glaucophyte plastids, that glaucophytes represent the first branch of plastid evolution.

Two other studies of nuclear genes support a monophyletic origin of plastids. Van

Molecular evolution

A single birth of all plastids?

Jeffrey D. Palmer

Amidst the present swirl of uncertainty about the correct branching order of the tree of life — or whether gene transfer between species on different branches is so pervasive as to make a coherent tree unattainable — a few conclusions about early evolution stand out as unassailable. Foremost among them is that plastids (the organelles in which photosynthesis occurs) and mitochondria (the cellular power plant, where respiration takes place) arose aeons ago from bacteria that set up home within other unicellular organisms, to mutual benefit. Only a die-hard creationist, by denying evolution itself, would deny that plastids and mitochondria are highly derived bacteria, with most of their genes having been either lost or transferred to the nucleus of the host cell. Although it is firmly established that plastids originated from cyanobacteria (Fig. 1), the number of such origination events is in dispute.

Primary plastids are the double-membrane-bound products of a symbiotic (mutually beneficial) relationship between eukaryotic cells (those with a nucleus) and cyanobacteria. Such plastids are found in three distinctive groups of eukaryotes — the green algae (including land plants), the red algae, and the glaucophytes (Fig. 1). Accumulating evidence from plastid^{1–3} and mitochondrial⁴ genomes favours a single (monophyletic) origin of the primary plastids, but the information from nuclear genes is at best equivocal^{1,5}. On page 69 of this issue, however, Moreira and colleagues⁶ report the first strong evidence from nuclear genes for a common origin of green- and red-algal plastids, and weaker evidence that glaucophyte plastids arose by the same event. These results are an important step towards universal acceptance of a monophyletic origin of plastids.

The study by Moreira *et al.*⁶ provides three mutually reinforcing lines of evidence for an affiliation of green and red algae. First, they analysed the evolutionary relationships (phylogeny) of nuclear genes encoding elongation factor-2, a protein involved in the

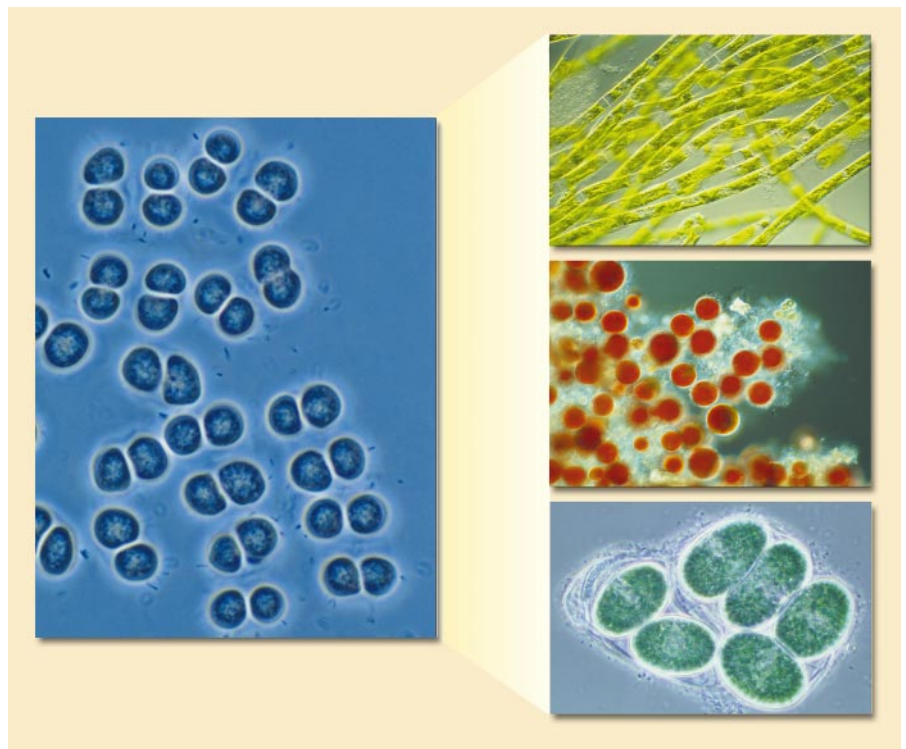


Figure 1 A single origin of plastids. Cyanobacteria (left, represented here by *Eucaopsis* sp.; magnification $\times 745$) probably gave rise to plastids of green algae (filaments of *Ulothrix fimbriata*; magnification $\times 120$), red algae (*Porphyridium* sp.; magnification $\times 77$), and glaucophytes (*Glaucocystis* sp.; magnification $\times 240$) through a single symbiotic event that took place over 1.2 billion years ago. This theory is supported by the work of Moreira *et al.*⁶. The photograph of *P. elegans* was provided by Astrid and Hans-Frieder Michler/Science Photo Library. The other photographs were provided by Michael Abbey/Science Photo Library.