needs to be defined better, as there could well be hazards in interrupting such signals. For instance, mice in which the gene encoding PD-1 has been inactivated develop spontaneous autoimmunity[4]. Moreover, Barber *et al.* report that infecting mice that lack PD-L1 with the persistent virus does not lead to clearance but rapidly to death, probably because of an overreaction of the immune system. Another danger was highlighted when two mouse strains were mated; when the resulting pregnant mice were treated with a similar antibody against PD-L1, they aborted a large fraction of the fetuses[5].

Although there were no harmful side effects when Barber *et al.* used antibodies to block the interaction between PD-1 and PD-L1, the authors are conscious that autoimmune disease might develop after prolonged disruption of this regulatory system. Their results provide further evidence of the delicate balance governing immune regulation and activation. ■

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EARTH SCIENCE

The rise and growth of Tibet

Andreas Mulch and C. Page Chamberlain

It is not difficult to be impressed by the grandeur of high mountainous regions, but it is difficult to reconstruct how the elevation of such regions evolved. A study of the Tibetan plateau does just that.

Is Everest now at its highest point, or was it once even loftier? What was the greatest height attained by the vast highlands of the Tibetan plateau, and when did this occur?

As described elsewhere in this issue by Rowley and Currie (page 677)[1], these questions can be tackled — if not yet answered definitively — by analysing the isotopic composition of ancient raindrops. With this approach, the authors show that Tibet continuously grew northward over millions of years in response to the thickening of Earth's crust associated with the collision of the Indian and Asian continental plates. The driving forces for this collision are generated deep in Earth's mantle. But the key to unravelling the uplifting history of the central Tibetan plateau is found in lake sediments on the plateau, some of which formed as long ago as 40 million years.

In these lakes and their surrounds, changes in the oxygen-isotope composition of surface water (which is controlled by regional climate and elevation) are recorded in sediments. Systematic variations in oxygen-isotope composition across the plateau reveal that spatially variable uplift of the plateau to 4,000 metres or more above sea level was intimately linked to the timing and rates of convergence of India and Asia (Fig. 1). Rowley and Currie[1] estimate that uplift to 4,000 metres was initiated as long ago as 40 million to 50 million years, in the early stages of that convergence.

The evolution of mountain topography reflects the balance between tectonic forces in Earth's crust and upper mantle, and climatically driven erosion at Earth's surface. Their relative role in controlling the rise of mountains remains unclear[2,3], but the problem can be approached by reconstructing the elevation history of large continental plateaux. Such studies can improve our understanding of the coupling between tectonics and long-term climate change. For example, the Tibetan plateau — the largest continental highland on Earth — is a major barrier to air flow in the atmosphere, and it has been suggested that uplift of the plateau triggered the onset of the Indian summer monsoon[3].

The chemical fingerprint of rain and snow that precipitated on the Tibetan plateau is found in the oxygen-isotope composition of calcareous minerals in Tibetan lake sediments. This is expressed as δ^{18}O, which is the ^{18}O/^{16}O ratio in the soils or sediments relative to the ^{18}O/^{16}O ratio in sea water. For example, the δ^{18}O of calcite formed in soils is related to the δ^{18}O of soilwater or groundwater by a temperature-dependent fractionation factor; so δ^{18}O in calcite formed in soil is a sensitive tracer of surface water that stems from precipitation. The underlying principle of oxygen-isotope altimetry is that water that precipitates as rain or snow becomes increasingly depleted in ^{18}O the higher up a mountain range that it falls[4]; systematic changes in δ^{18}O with elevation can then be used to infer relative elevation differences between the water source in the ocean and the elevation at which the rain or snow fell[5,6].

In the context of earlier isotopic studies[6,7], the low δ^{18}O values of carbonates found by Rowley and Currie[1] across the central Tibetan plateau reflect the south–north migration of high terrain in response to crustal thickening and the buoyant rise of Earth's surface. This finding agrees with the results of thermomechanical modelling for the growth and uplift history of the Tibetan plateau[8].

It was proposed previously that the present stature of Tibet reflects tectonic processes involving thinning and delamination of Earth's crust and mantle during the Miocene (10 million to 8 million years ago)[3]. But it has since been suggested[9,10] that the sequential rise and northward growth of Tibet started much earlier than that, in Eocene times, about 50 million years ago. The new results[1] support this idea that the Tibetan plateau is a long-standing topographic feature that arose from the collision between India and Asia, and is not the more recent product of other, deeper-seated processes. The results also show that stable isotopic data from sedimentary sequences do indeed record the long-term, high-elevation history of the plateau, and can provide absolute elevation constraints at

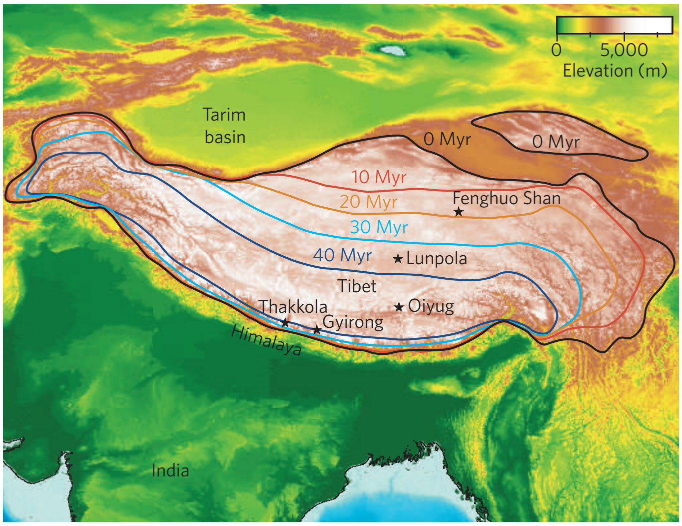

Figure 1 | Elevation history of the Tibetan plateau. According to Rowley and Currie's analysis[1], elevations of 4,000 metres or more were established as early as 40 million years (Myr) ago, with Tibet then growing northward over time. Solid lines show the development of the 4,000-metre contour as derived from oxygen-isotope data from the Thakkola, Gyirong, Oiyug, Lunpola and Fenghuo Shan sedimentary basins[1,5–7]. The questions posed at the start of this article remain unanswered, however: the elevation history of Everest and the high Himalayan peaks has yet to be unravelled. (Figure courtesy D. B. Rowley.)

various times in the geological history of such a topographic feature. Moreover, taken in conjunction with independent estimates of palaeoelevation[11], this approach overcomes some of the limitations in deciphering the competing effects of climate and elevation change in the past.

Only slowly are we making progress in understanding how the interactions of surface uplift, bedrock erosion and sediment transport create dynamic feedbacks between the biosphere, the atmosphere and the crust and upper mantle. However, new techniques for estimating palaeoaltimetry that relate processes at various levels of Earth's crust, from the surface to deeper regions where high-temperature deformation causes rock flow, will allow us to develop a more dynamic view of how mountain ranges change their shape and stature. Such techniques exploit elevation-dependent changes in concentration of carbon dioxide in the atmosphere[12], or the isotopic composition of surface waters that circulate deep in Earth's interior during the late tectonic evolution of mountain ranges[13].

Deciphering the oxygen-isotope record in lake and soil deposits requires careful consideration of the competing effects of climate change and changes in surface elevation. The application of multi-proxy isotopic systems, which take account of both surface and deeper Earth environments, can complement such studies and greatly enhance our predictive capabilities in such a task. ■

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SEMICONDUCTOR PHYSICS

Transport news

John J. Boland

Conventionally, conduction in silicon is enhanced by doping — adding impurities that change the material's electronic structure. But exploiting surface effects in thin silicon films may offer yet other opportunities.

Silicon-based electronics continues to obey the dictum known as Moore's law: that the density of transistors on an integrated circuit — a rough measure of the attainable processing power — doubles about every 18 months. As the size of the smallest features of a device approaches the nanoscale, the electronic properties of the constituent materials are increasingly affected by the surrounding surfaces and interfaces. This can sometimes have deleterious effects on the transport of charge carriers — and so on device performance. On page 703 of this issue, Pengpeng Zhang and colleagues[1] show how surface effects can in fact be used to control conduction in silicon membranes. Their results potentially provide a new route to nanoscale materials and devices.

The continued drive towards higher device densities on silicon chips requires not only lithographical techniques that can define ever-smaller device features, but also the ability to manipulate precisely the Fermi energy of electrons in silicon, conventionally achieved by the process of doping (Box 1). But surfaces and interfaces are known to affect the electronic properties of silicon too. For instance, electrons from surface atoms can establish themselves within silicon's band gap, in which there are normally no allowed electronic states. There they can trap or deplete charge carriers, and so affect the position of the Fermi energy. Having the correct surface passivation chemistry — that is, the right sort of chemical bonds on the surface to eliminate mid-gap states — minimizes the effect of these rogue states. For silicon, an exceptionally low density of interface traps is achieved by an interface with an insulating layer of silicon oxide, SiO_2. In this case, provided the dopant level is high enough, at most only a few silicon layers adjacent to the interface are depleted of carriers. The position of the Fermi energy is still controlled by the dopant concentration in the bulk of the material.

This interplay between doping and interface states is a fundamental aspect of device physics, and becomes even more important when small structures are involved[2]. Then, the lower total number of atoms, the increasing fraction of surface and interface atoms and the dopant population combine to provide an interesting mix. One possible consequence is fluctuation in the number of dopant atoms incorporated into the silicon, resulting in unacceptable variations in device performance across the wafer.

A possible solution to this problem is the development of high-resolution techniques that enable dopant ions to be implanted into the semiconductor material one by one[3]. But even if the dopant density could be controlled so precisely, the nanoscale membranes would eventually become so thin that even the low density of traps afforded by the SiO_2 interface would deplete the device of carriers, rendering it unworkable. Such effects have long been regarded as a fundamental limitation on the minimum size and thickness of silicon-based devices.

Zhang and colleagues[1] use a combination of

Box 1 Bands, holes and flows

In any solid material, the atomic orbitals that determine the properties of the electrons in an atom combine to form bands of allowed energy levels. Electrons fill these levels two-by-two following rules laid down by quantum mechanics. The energy up to which the allowed energy levels are filled is known as the Fermi energy. If this energy lies within a band of allowed energy levels, the material is a conductor; if it lies in a gap between allowed energy levels, the material is a semiconductor or insulator.

In a semiconductor, the gap between the completely filled 'valence' band and the completely empty 'conduction' band is small (about 1 electronvolt). So, whereas at low temperatures these materials are insulators, at normal temperatures a small population of electrons can be excited thermally from the valence band to the conduction band. The electrons create a negatively charged flow of current in the conduction band; equally, the electron deficiencies they leave behind — known as 'holes' — give rise to what is in effect a positively charged flow of current in the valence band.

The number of electrons or holes can be tailored by adding so-called dopant atoms to the semiconductor. In a silicon crystal, with its four valence electrons per atom, this doping may be achieved in one of two ways. First, by introducing atoms of an element such as phosphorus, antimony or arsenic that has a fifth electron (n-type doping). These extra electrons will occupy energy states close to the conduction band, into which they are easily excited to contribute to conduction. Second, doping may be effected by introducing an impurity possessing only three electrons, such as boron, aluminium or gallium (p-type doping). This creates energy states close to the valence band, into which electrons can jump, leaving behind holes in the valence band. **J.J.B.**