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AAPG Petroleum Structure and Geomechanics Division (PSGD)

Best Seminal Publication Award 2020

Response to Citation by Peter Hennings

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We would like to first of all thank Peter Hennings for his generous citation and to the *Petroleum Structure and Geomechanics Division* of the *AAPG* for this Best Seminal Publication Award for our papers on the mechanics of thrust belts and accretionary wedges. This award also honors our coauthor, the late Tony Dahlen (1942-2006) who was one of the most creative theoretical geophysicists of the late 20th Century. A 1986 photograph (Fig. 1) shows the three of us with a small bulldozer that created a human-scale accretionary wedge of soil. We were all at Princeton together where this work on critical-taper wedge mechanics was spawned by Dan's 1978 Senior Thesis. A key ingredient was Florian Lehner who had come to Princeton from Georg Mandl's structural geology research lab at Shell in Rijswijk. Shell was known at the time for its strength in experimental structural geology and geomechanics, which went back to M. King Hubbert and other notables. Florian convinced John that careful analog deformation experiments using suitably prepared dry sand could give excellent quantitative insight into the deformation of sedimentary basins, particularly because of the first-order scale independence of sand as a Coulomb frictional material. Dan was in search of a Senior thesis topic and Florian suggested that Dan might do some experiments on the mechanical development of foreland thrust belts, which was of particular interest to us, stimulated by a lecture that Bill Chapple had given at Princeton as part of a geomechanics lecture series. Dan, armed with a budget of fifty dollars, developed an exceedingly simple apparatus capable of large deformation in which layers of

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sand were deformed into imbricated thrust belts above a low-friction Mylar detachment. The entire apparatus could be tilted to vary the dip of the detachment. Remarkably, these experiments showed that the sand thrust belt deformed until it reached a critical surface slope that covaried linearly with the detachment dip. Dan then developed an approximate static-equilibrium theory showing that the critical tapers and their variation with detachment dip were those predicted by his independent measurements of the internal friction of sand and the sliding friction of sand on Mylar, demonstrating a link between pressure-dependent strength and wedge geometry.

These results of Dan's thesis were particularly exiting to John because of their scale independence, suggesting that the theory could be applied at the scale of mountain belts if we knew the tapers and the fluid pressures. The next year John was fortunate to be on sabbatical leave in Taiwan where he set about to measure the regional surface slope, detachment dip and pore-fluid pressures of the active western Taiwan fold-and-thrust belt with help from the Chinese Petroleum Corporation. The fluid pressures were needed to make the leap from dry-sand wedges in the lab to active thrust belts. This eventually led to the 1983 Davis-Suppe-Dahlen paper, which Tony joined at the writing stage when he realized that he could develop an exact formulation of wedge mechanics, which he followed with a series of papers that eventually led to his powerful approximate-general formulation in 1990.

These early results in wedge mechanics opened the door for wide-ranging applications to the Earth. In particular, analog and numerical experiments in wedge mechanics became very popular and sophisticated, eventually including thermal and surface-process modeling, with a variety of rheologies, which have been applied powerfully to specific ancient and modern plate-boundary and passive-margin settings, both in compression and extension. Most of the applications until recently have been conceptual, qualitative, or semi-quantitative, which reflects a conceptual power but also an unintended weakness inherent to the original formulation in terms of observables. From the very start we were interested in addressing the then current controversy over the order of magnitude of stress or strength in the upper crust.

Was it high, as suggested by Byerlee friction, or was it an order of magnitude lower, similar to the then current estimates of stress drops of earthquakes? For this reason, we wrote the wedge equations in terms of familiar rock-mechanics quantities, which made them quite complex. As a result, our applications to the Earth, including Taiwan and Barbados, consisted of trying to carve out regions of a complex parameter space that satisfied observed tapers and any other constraints we could cobble together. In retrospect this was a bit unfortunate, because we now realize that in many cases we can avoid the rock mechanics formulation entirely and go directly from observed wedge geometries to depth-normalized strengths, expressed as an effective coefficient of friction on the detachment and a wedge strength analogous to the earth-pressure coefficient used in soil mechanics. This is essentially what Dan was doing in his senior thesis with sand wedges on Mylar; we now observe that active earth wedges show the same covariation of critical surface slope with detachment dip, confirming wedge theory for natural wedges and supplying large-scale measurements of the strengths of active wedges and their detachments. By now, the door has been opened for more quantitative applications of wedge theory to the Earth, based on the sort of observables familiar to the members of the *AAPG PSGD*, which are obtained from seismic imaging and velocity analysis, from petroleum and scientific borehole measurements, and from stress orientations from seismology within actively deforming wedges, as well as post-earthquake drilling of principal slip zones of large wedge-earthquakes. We would like to acknowledge the contributions of the petroleum industry to our growing understanding of the mechanics of deformation of sedimentary basins, which has been key to the development and growth of critical-taper wedge mechanics. Thank you all!

Fig. 1. A human-scale bulldozer wedge (1986) with Dan Davis (right), Tony Dahlen (center), and John Suppe (left).