Using a continuous laser system, we have obtained high-resolution $^{40}Ar/^{39}Ar$ age spectra on single fragments of 12 melt rock samples from the Apennine Front. The melt rocks, all fine-grained, are essentially aluminous basalts, but with a variety of compositions, e.g., MgO 9 to 21%, Sm 2 to 25 ppm. We believe they must represent at least several different impact events. A few milligrams of each sample were crushed to submillimeter sizes and individual fragments, visibly free of clasts and weighing 62 to 620 mg, were irradiated. They were analyzed with a continuous Ar-ion laser extraction system and mass spectrometer [10,11]. Individual particles were incrementally heated, with temperature measured with an infrared radiometer. We have obtained 26 age spectra on the 12 melt samples. Some of these results have been previously published [11].

Of the 12 rocks analyzed, 7 have age spectrum plateaus that we interpret as crystallization (impact) ages. Individual plateaus have 2-sigma uncertainties of ±16 Ma. The $^{40}Ar/^{39}Ar$ plateaus are generally well defined in the intermediate temperature range with 40% to 70% of the ^{39}Ar released. Six of these ages fall within the narrow range of 3879 Ma and 3849 Ma, more or less within uncertainty of a common age. Spectra on five fragments of one sample gave a range from 3856 Ma to 3879 Ma. The seventh sample gave a plateau age of 3836 Ma. The total span of ages is less than 1%, a very narrow range. The remaining five samples show spectra that clearly indicate disturbance by post-3.8-Ga events, and lack plateaus. None of the 26 age spectra for the 12 melt rocks show any indication of older melt components. A conventional $^{40}Ar/^{39}Ar$ age of 3.85±0.05 Ga for a different impact melt from the Apollo 15 landing site was reported by [12].

We believe that these data provide ages for a variety of impact melts that are coeval with or predate the Imbrium event. Thus a first-order conclusion is that the Imbrium event is no older than about 3870 Ma, and probably no older than 3940 Ma. Independent evidence suggests strongly that Imbrium is not younger than this (because of the later KREEP basalts), hence is indeed very close to 3840 to 3850 Ma. In that our data show a variety of melts at or just before this time but not older melt, we believe it to be consistent with a very tightly constrained bombardment of the Moon. Serenitatis (about 3.87 Ga) falls in this same period. We have still no tangible evidence for significant bombardment prior to 3.9 Ga.

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SEARCH FOR THE 700,000-YEAR-OLD SOURCE CRATER OF THE AUSTRALASIAN TEKTITE STREWN FIELD.

C. C. Schnetzler[1] and J. B. Garvin[2], [1]Geography Department, University of Maryland, College Park MD 20742, USA, [2]Geodynamic Branch, Code 921, Goddard Space Flight Center, Greenbelt MD 20771, USA.

Many tektite investigators have hypothesized that the impact crater that was the source of the extensive Australasian strewn field lies somewhere in or near Indochina. This is due to variations in abundance and size of tektites across the strewn field, variation of thickness of microtektite layers in ocean cores, nature of ablation characteristics across the field, and, above all, the occurrence of the large, blocky, layered Muong Nong-type tektites in Indochina. A recent study of the location and chemistry of Muong Nong-type and splash-form tektites suggests that the source region can be further narrowed to a limited area in eastern Thailand and southern Laos [1].

There are four lines of evidence that point toward this area. The first is the observation that tektite sites in Indochina are nonrandomly distributed. Many sites seem to be located along linear trends or "rays" separated by areas relatively sparse or devoid of samples. These rays converge to a small area along the Thailand-Laos border between 15.5°N and 17°N latitude. Second, there is a somewhat larger region, enclosing the area delineated by the rays, where Muong Nong tektites predominate and/or there is no mention of splash-form-type tektites. Third, a high proportion of the reported sites containing super-sized (>1 kg) Muong Nong tektites are in this area. Lastly, Muong Nong tektites with this area show the largest chemical inhomogeneity in sites, and there is a high chemical gradient across the region; these are characteristics one would expect proximal to the source. The area defined by the above evidence is centered at 16°N/105°E, with a radius of approximately 125 km.

Satellite multispectral imagery, a digital elevation dataset, and maps showing drainage patterns have been used to search within this area for possible anomalous features that may be large degraded impact craters. Four interesting structures have been identified from these datasets:

1. An approximately 30-km-diameter, quasicircular structure in Laos, resembling a partially infilled impact structure, centered at 16.35°N/106.15°E. It has a relatively flat floor surrounded by hills rising 70 m to several hundred meters above the floor, and a central elevated area rising about 100 m above the floor (Fig. 1). The structure is breached at approximately the cardinal points by rivers.

2. An approximately 25-km-diameter circular feature on the east side of the Mekong River, slightly east of Savannakhet, Laos (16.55°N/104.90°E). This feature is not an obvious depression or crater, but is an approximately circular area enclosing hummocky terrain of very low relief.

3. A 90-km-diameter area, centered at 16.6°N/105.5°E (directly to the east of structure 2). This broad south-sloping feature is rimmed by high hills on the north and east, rising to 450 m above the floor, but only low lying hills to the west and south. The area is drained by two rivers flowing to the south.

4. An oblong depression on the west side and in a curve of the Mekong River, approximately 80 km northeast of Ubon Ratchathani, Thailand. It is approximately 30 km long northwest-southeast, and about 20 km wide southwest-northeast. Hills rise about 75 m in the southwest to over 300 m in the southeast above the flat floored plain.
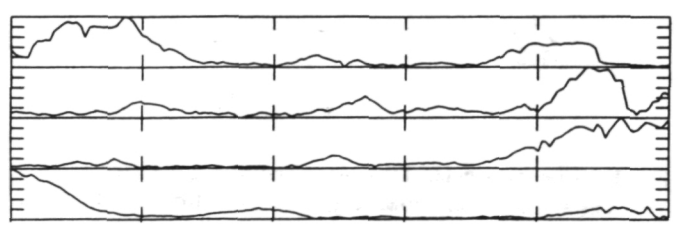

Fig. 1. Profiles across structure 1, centered at 16.35°N/106.15°E, in southern Laos. From top to bottom, southeast-northwest, southwest-northeast, west-east, south-north.

All these features lie within a broad region of Mesozoic marine sedimentary rocks, the Indosinias formation, primarily sandstones interbedded with shales and limestones, which covers much of central Indochina. The age and composition of these sediments are broadly consistent with Australasian tektite composition and age [2]. Field work to examine these structures and collect country rocks for specific comparisons would seem warranted.

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RECOGNIZING IMPACTOR SIGNATURES IN THE PLANETARY RECORD.

Peter H. Schultz[1] and Donald E. Gault[2], [1]Department of Geological Sciences, Brown University, Providence RI, USA, [2]Murphys Center of Planetology, Murphys CA, USA.

Crater size reflects the target response to the combined effects of impactor size, density, and velocity. Isolating the effect of each variable in the cratering record is generally considered masked, if not lost, during late stages of crater modification (e.g., floor uplift and rim collapse). Important clues, however, come from the distinctive signatures of the impactor created by oblique impacts.

In laboratory experiments, crater diameter exceeds impactor diameter by a factor of 40 for vertical impacts into gravity-controlled particulate targets and reduces to 25 for oblique impacts at 15° from the horizontal. Strength-controlled cratering in aluminum reduces these factors to 5 and 2 respectively. As scale increases, crater excavation is limited by gravity and cratering efficiency becomes progressively less efficient. A 100-km-diameter crater on Earth (rim-to-rim diameter with 25% enlargement due to slumping) is only a factor of 12 greater than the impactor diameter for a vertical impact and reduces to 6 for a 15° impact angle based on scaling relations given in [1]. The early compression stage [2] at planetary scales, therefore, comprises a significant fraction of the final crater size and approaches a value more typical of strength-controlled laboratory experiments, particularly for oblique impacts.
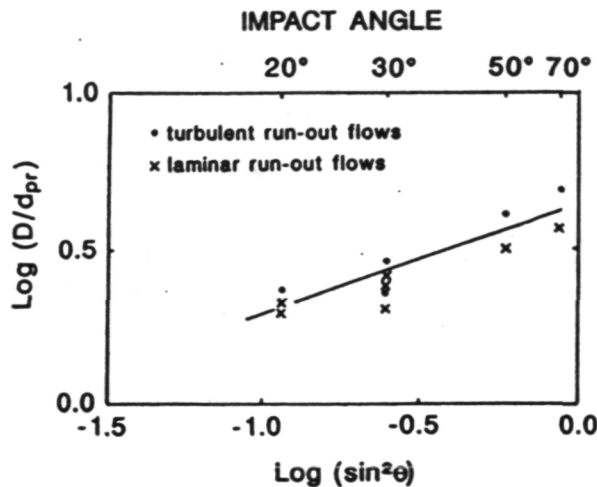
As a result, the distinctive signatures of early energy transfer may not be completely consumed by crater growth at planetary scales.

Two key diagnostic features of oblique impacts can be found in craters at both laboratory and planetary scales. First, oblique impacts create a distinctive asymmetric crater profile with the deepest penetration and steep inner wall uprange and a shallow, shelflike wall downrange [3]. Such a profile occurs for impact angles from 45° to 15° in strength-controlled craters (e.g., aluminum targets) but requires impact angles less than 5° for gravity-
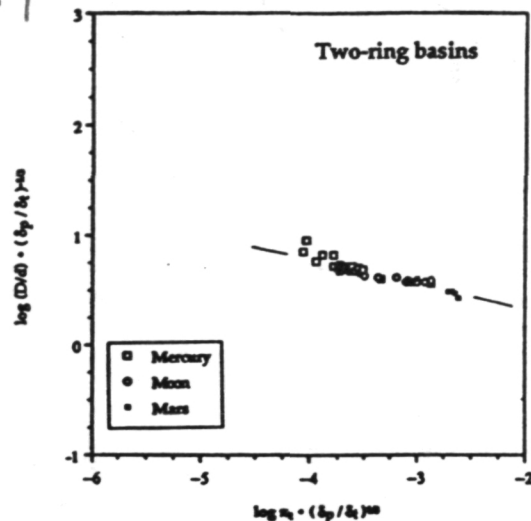

Fig. 2a. Crater diameter (D) scaled to impactor diameter (d) inferred from peak-ring diameter as a function of the dimensionless gravity-scaling parameter π_2 equal to $3.22\ gr/v^2$ with radius (r) again inferred from peak-ring diameter (g and v refer to gravity and impact velocity respectively; δ_p/δ_t represents projectile/target density ratio). Data for the Moon, Mercury, and Mars collapse onto a single relation for impact velocities 14, 16, and 32 km/s respectively.
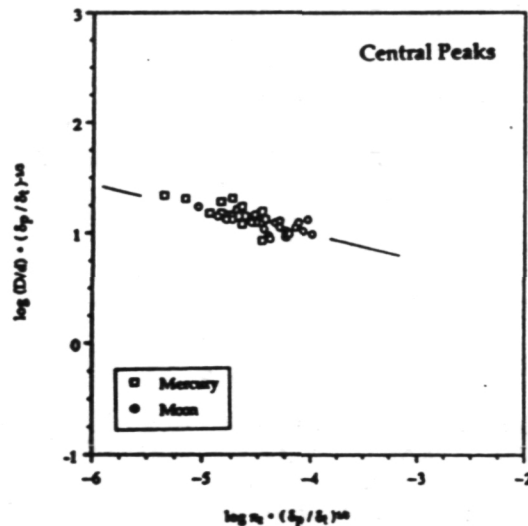

Fig. 1. Crater diameter (D) scaled to peak-ring diameter (d_{pr}) on Venus as a function of impact angle estimated from the degree of asymmetry in the ejecta deposits. If peak-ring diameter depends on impactor size (given velocity), D/d_{pr} should decrease as impact angle decreases, as is shown. Different symbols correspond to different styles of long run-out flows observed on Venus [6].

Fig. 2b. Crater diameter scaled to impactor diameter as in Fig. 2a but referenced to the diameter of the central peak. Assumed impact velocities for the Moon and Mercury in this case are 16 and 40 km/s respectively.