Contractionally deformed belemnites as indicators for thrust faulting in mechanically weak sedimentary layers
An example from the Lower Cretaceous of the Talkeetna Mts., Central Alaska

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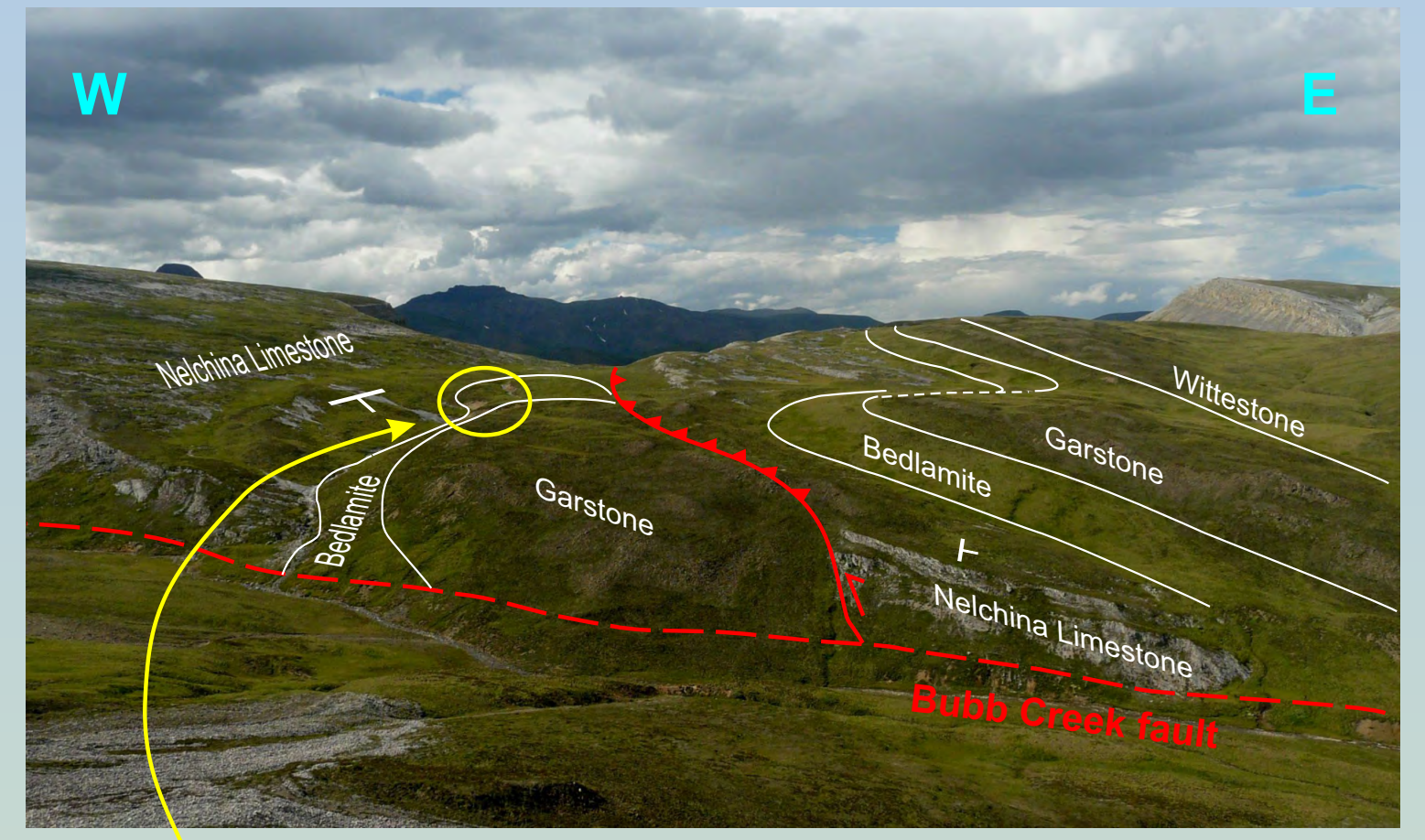
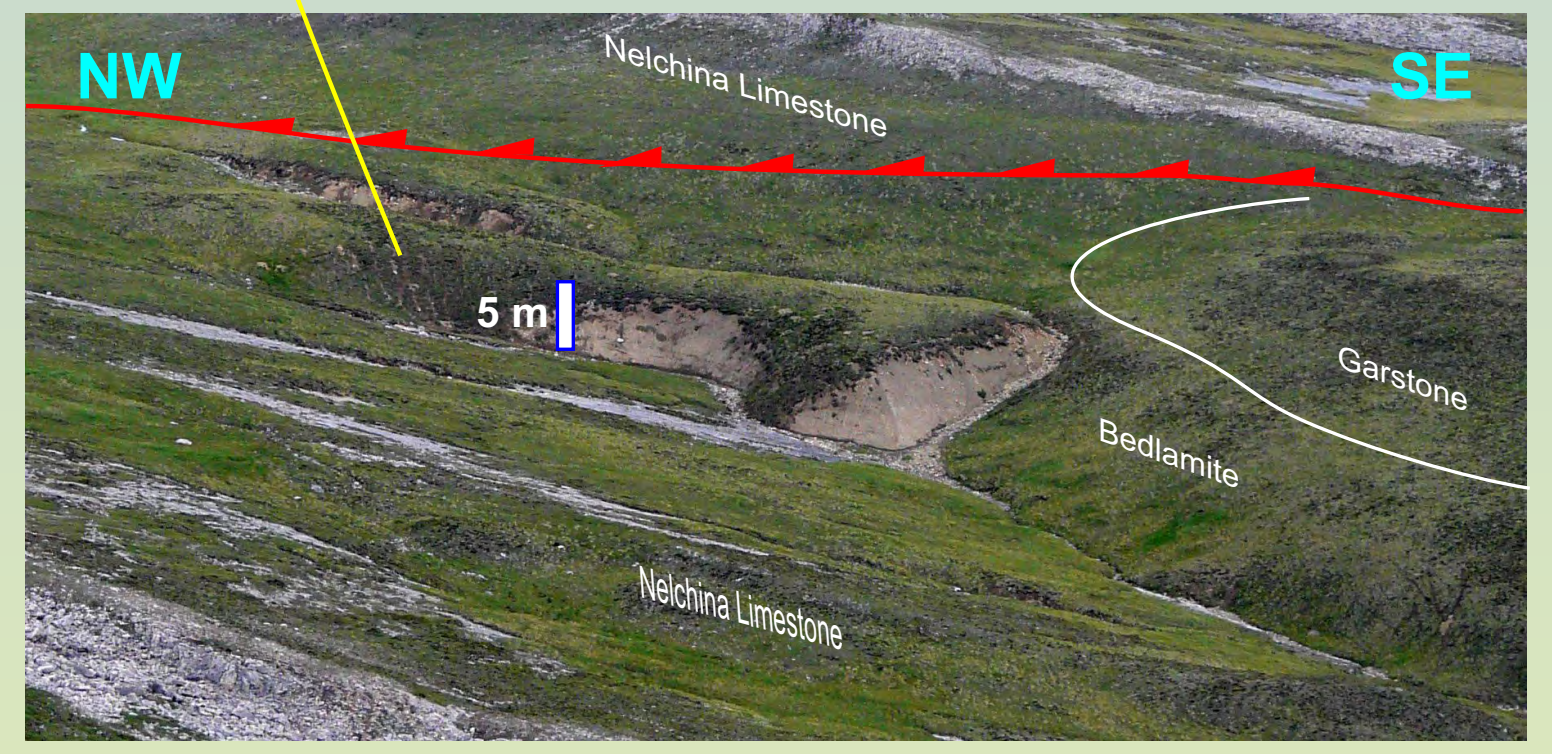
Introduction

Stretched belemnites, more precise, the rod-shaped guards or rostra that form the internal skeleton of the rear third of a squid-like cephalopod, have been observed in Jurassic slate and limestone of the French and Swiss Alps. The rostrum is made up of radiating fibrous calcite crystals oriented with their long axes perpendicular to that of the rostrum (see photo above), resulting in low tensile strength. When subject to extension, the belemnites fracture and form boudins, i.e. they deform in a brittle fashion and the spaces between the fragments are filled by quartz/calcite fibers or matrix material. Elongation can easily be determined and used for strain analyses (Badoux 1963; Ramsay 1967; Hossain 1979; Beach 1979; Lloyd & Ferguson 1989). Many students are probably familiar with the practical strain measurement problems involving belemnites in volume 1 of Ramsay & Huber's "Techniques of Modern Structural Geology".



Eastward dipping sedimentary sequence of the resistant Nelchina Limestone, the more recessive Belamite calcareous mudstone, the Garstone sandstone and the Wittestone. The Bedlamite outcrop is the only locality with a decent exposure of the calcareous mudstone. In other places, strong susceptibility to weathering results in recessive erosion, overgrown slopes and concealed by sandstone debris from the overlying Garstone unit. Belemnites are washed out of the mudstone and accumulate in the gully formed at the contact with the underlying hard Nelchina Limestone. Note the westward directed reverse fault (red line with arrows pointing downdip) cutting across the Bedlamite-Garstone contact.

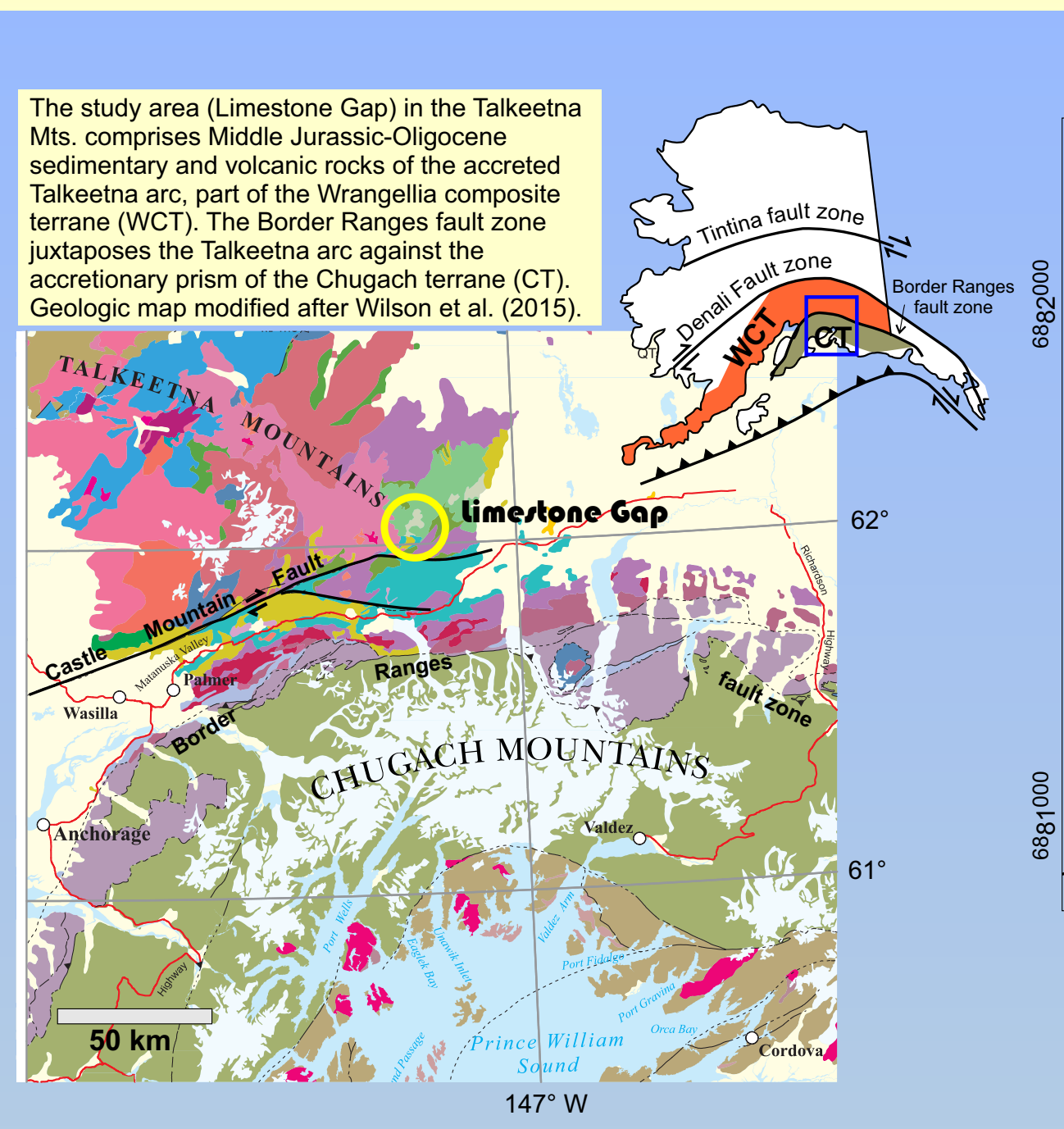


Limestone Gap in the Talkeetna Mountains

The rocks that underlie the Talkeetna Mountains in south-central Alaska are part of the large Wrangellia composite terrane (WCT), which accreted to North America in the late Mesozoic. The Talkeetna Arc comprises Jurassic oceanic arc sediments, Cretaceous-Oligocene forearc basin sediments and Eocene volcanic rocks (Trop 2008). Subsequent accretion of the Chugach terrane to the south and the development of major strike-slip faults in the Paleogene (Denali and Castle Mountain faults) are testimony to significant longlived tectonic activity.

The immediate study area in the eastern Talkeetna Mountains is controlled by kilometer-scale open folds of the massive and resistant Nelchina Limestone, forming plateaus that cap the kilometer thick sequence of the Naknek Formation. Locally known as Limestone Gap, the ideal morphology and the proximity to the Glenn Highway are the reasons why this area is the location of the capstone mapping project of the Geology Field Camp of the University of Alaska Fairbanks.

Overlying the Nelchina Limestone are belemnite-bearing calcareous mudstone ("Bedlamite"), sandstone ("Garstone"), siltstone ("Wittestone") and sandstone with coal seams ("Seabee"). None of these units have been mapped individually. They are included in the Nelchina Limestone map unit of Trop (2008). The informal names used in this poster originate from the UAF Geology Field Camp.

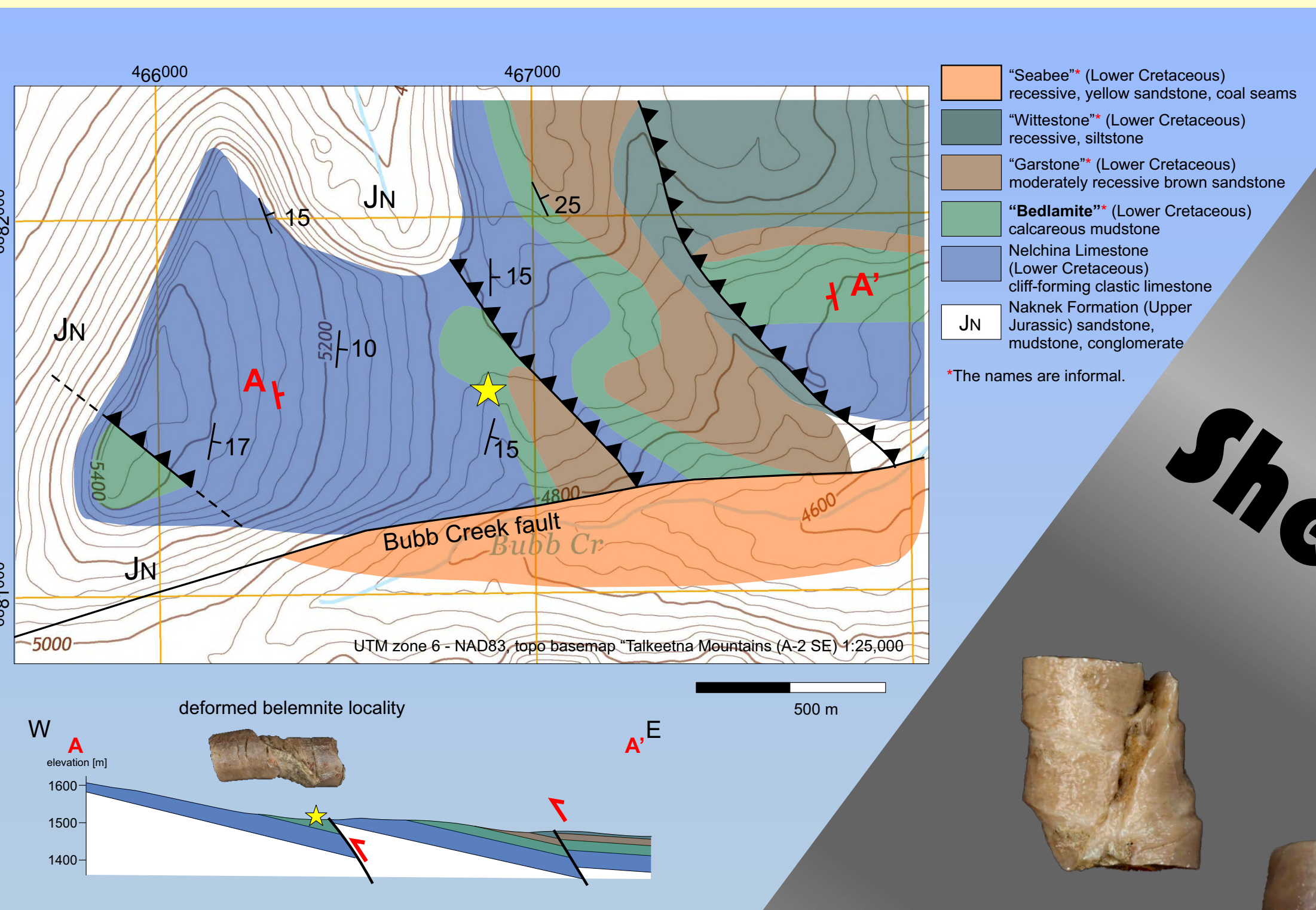


The study area (Limestone Gap) in the Talkeetna Mts. comprises Middle Jurassic-Oligocene sedimentary and volcanic rocks of the accreted Talkeetna arc, part of the Wrangellia composite terrane (WCT). The Border Ranges fault zone juxtaposes the Talkeetna arc against the accretionary prism of the Chugach terrane (CT). Geologic map modified after Wilson et al. (2015).

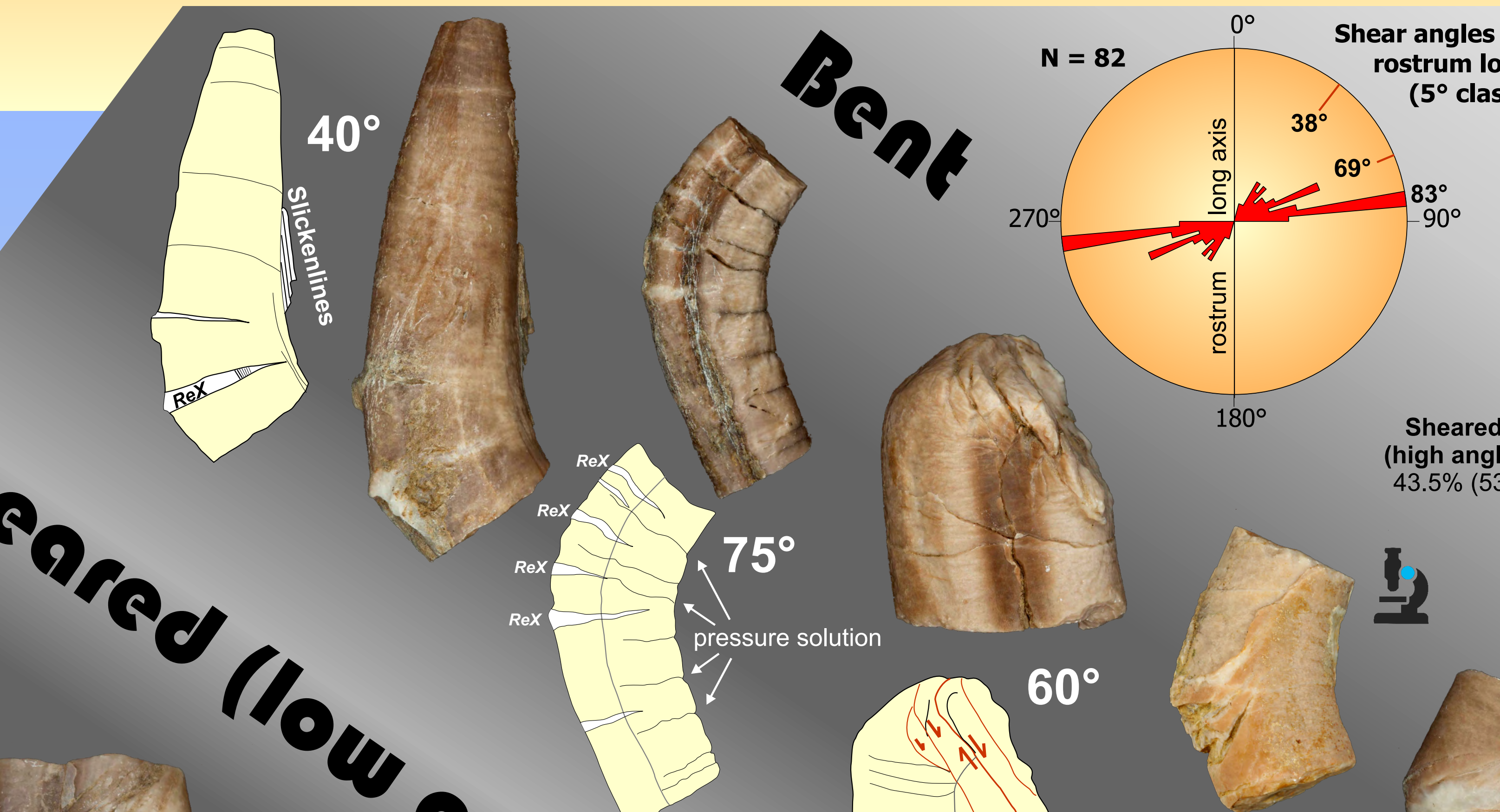
In contrast to stretched belemnites, there is very little to be found in the scientific literature about belemnites having experienced ***contractional deformation***, with bent or sheared rostra. It is unclear if that is owed to an actual scarcity or reflects a bias, i.e. indifference of structural geologist towards fossils and invertebrate palaeontologists towards deformation.

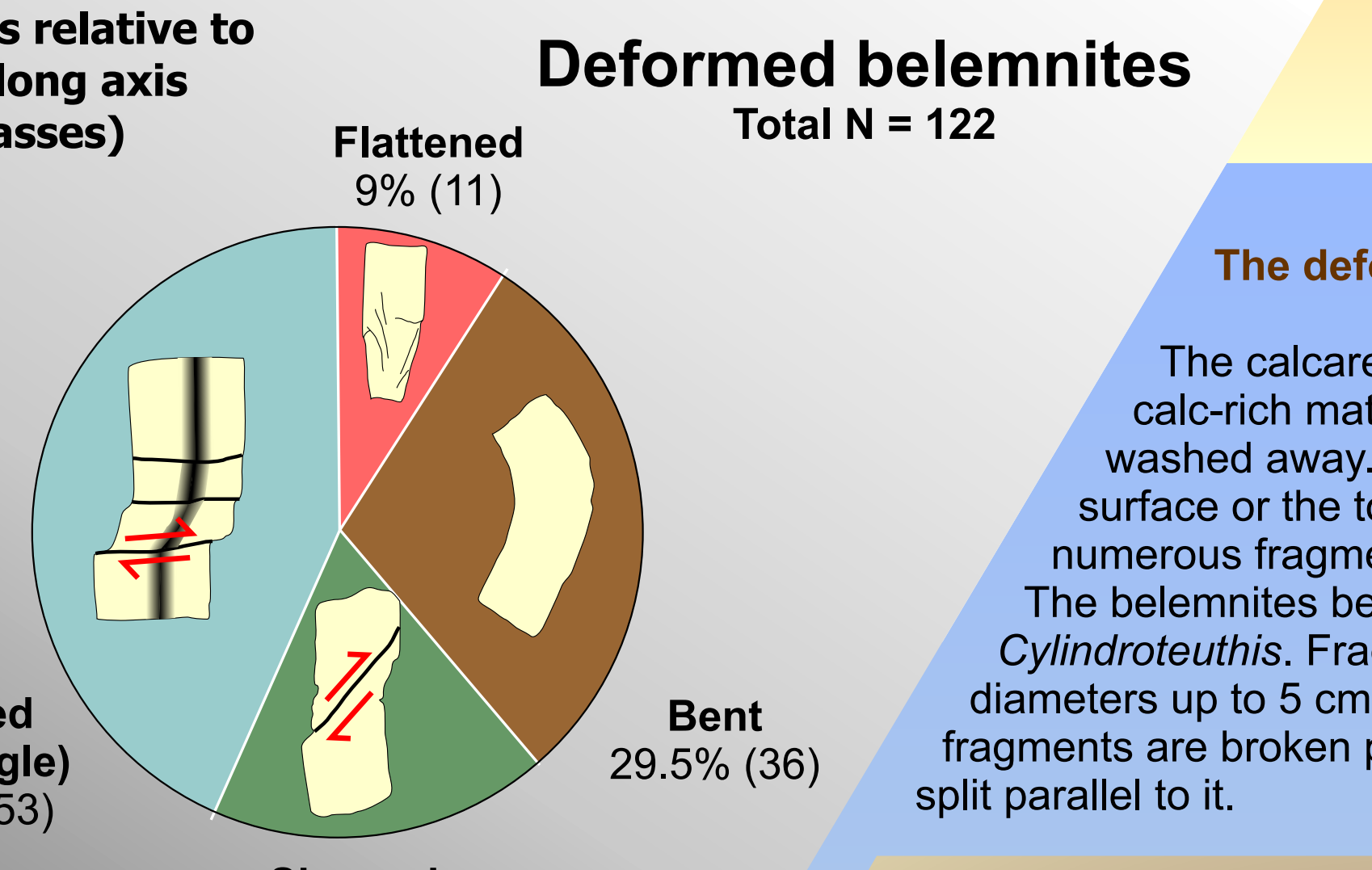
The only reference I am aware of dates to Hüttner (1969) who described sheared belemnites from Jurassic shale within the Ries meteorite crater in Bavaria. Hüttner concluded that the deformation was the direct result of the meteorite impact in the Miocene! Recent finds in central Alaska which are presented here question this theory.

The calcareous mudstone of the Bedlamite is extremely susceptible to weathering, due to its high calcite content. However, after digging half a meter into the slope a much stronger less altered mudstone is revealed. It appears to be very brittle and fractured. It is not possible to expose continuous bedding layers.



Regional geologic map showing the fossil locality and the proximity of the belemnite-bearing "Bedlamite" calcareous mudstone to reverse and thrust faults that cut across the limestone-marl-sandstone sequence. The dip of the reverse faults is not exactly known and only estimated from exposure-topography relations.





The deformed belemnites of Limestone Gap

The calcareous "Bedlamite" mudstone is very recessive, its calc-rich matrix easily dissolved and the remaining clay washed away. Left behind and concentrated on the present surface or the top of the underlying massive limestone are numerous fragments of belemnite rostra and mollusk shells. The belemnites belong to the lower Cretaceous species *Cylindroteuthis*. Fragments are up to 10 cm long with diameters up to 5 cm. The overwhelming majority of the fragments are broken perpendicular to the rostra long axes or split parallel to it.

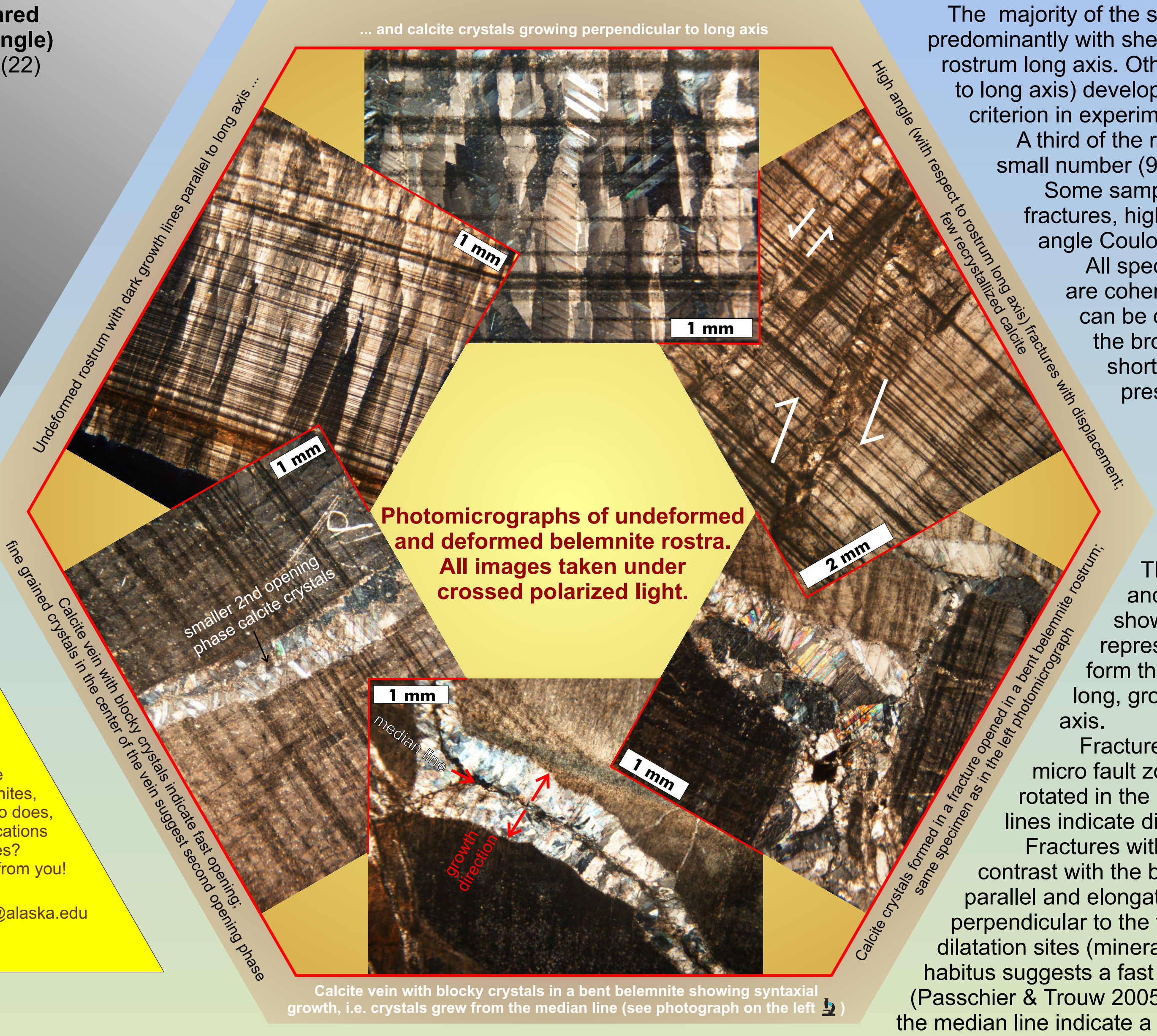
Amongst short belemnite rods, the occasional odd-shaped belemnite fragment - folded, flattened or sheared - stand out. The abundance of such deformed belemnite rostra is difficult to estimate, but several hours of collecting at two localities yielded over 120 specimen. Representative rostra of the nicest specimen covering the variety of deformation types are shown on the main photograph plate, along with interpretive sketches outlining the deformation structures.

The majority of the samples (60%) are sheared, predominantly with shear planes at high angle to the rostrum long axis. Others resemble shear fractures (< 40° to long axis) developed under the Coulomb fracture criterion in experimental rock deformation experiments.

A third of the rostra are bent, up to an angle of 75°. A small number (9%) of belemnites are flattened.

Some samples show two generations of shear fractures, high angle shears being overprinted by low angle Coulomb shear fractures.

All specimen have in common that the deformed rostra are coherent, held together by recrystallized calcite, which can be distinguished by its light grey to white color from the brown of the original rostrum. Fractures on the shortening side of folded belemnites are indicative of pressure solution.



Photomicrographs of undeformed and deformed belemnite rostra. All images taken under crossed polarized light.

Calcite vein with blocky crystals in a bent belemnite showing syntaxial growth, i.e. crystals grew from the median line (see photograph on the left)

Thin section analyses

Thin sections were prepared from several sheared and bent belemnites. Undeformed parts of the rostrum show dark thin lines parallel to the long axis, representing growth rings. The calcite crystals that form the rostrum are up to 1 mm wide and several mm long, growing radial and perpendicular to the long axis.

Fractures are developed as sub-millimeter wide micro fault zones with fragments of the rostrum rotated in the manner of fault blocks. Displaced growth lines indicate displacement and sense of motion.

Fractures with newly crystallized colorless calcite contrast with the brown calcite of the skeleton. Their parallel and elongated prisms indicate growth perpendicular to the fracture, characteristic of dilatation sites (mineral veins). Their general blocky habitus suggests a fast opening syntaxial growth (Passchier & Trouw 2005). Smaller crystals around the median line indicate a second opening phase.

Help!

Do you have deformed belemnites, know someone who does, know of any publications or field localities? I would love to hear from you!

Contact me: jemezger@alaska.edu

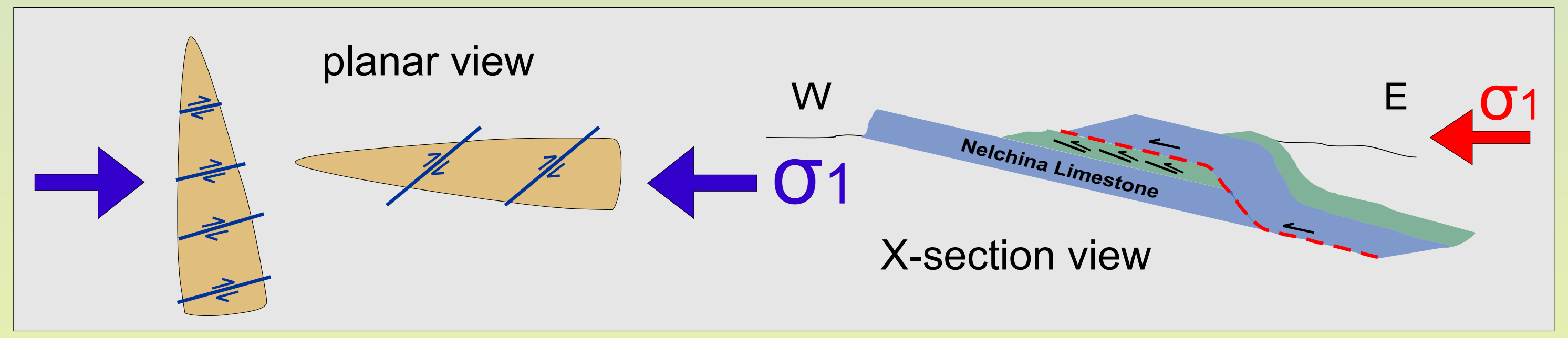
Thank you!!

Strain markers?

After death of a belemnite, its rostrum came to rest horizontally on the surface of the ocean floor, and assuming the absence of strong bottom currents, without alignment. After diagenesis, the rostrum's orientation is parallel to bedding, but random in X and Y directions.

The presence of calcite veins - several generations in some samples - preserving the coherence of the deformed belemnite rostrum strongly suggests that the fossils experienced continuous deformation over a certain period.

Unfortunately, the outcrop conditions do not reveal any deformation fabrics within the Bedlamite mudstone. Also, the belemnites are not found in place at the Limestone Gap outcrops, not allowing reconstruction of *in situ* orientation of the rostra or strain analyses. Assuming random orientation within the bedding plane, the high and low angle shear fractures can be attributed to the initial different orientation of the rostra long axes. Both high and low angle shears can be explained by one stress direction (σ1). Overprinting shear fractures could hint at changes in the main compressive stress or rotation of the fossil. Some rostra are crushed, indicating that flattening (related to diagenesis or vertical tectonic stress?) also affected the fossils. Some high angle shear fractures might be the result of flattening. Clearly, there is still much to investigate.



Possible formation of belemnite fracture shears and associated tectonic model. The thin and relative weak calcareous mudstone is wedged between stronger massive layers (Nelchina Limestone and/or Garstone) and serves as glide horizon in duplex structures. Internal deformation within the mudstone accommodates some of the strain resulting from west-directed compressive stress.

Tectonic indicators?

The Bedlamite calcareous mudstone layer is thinner (10-15 m) and weaker than the underlying Nelchina Limestone (30-40 m) or the overlying Garstone sandstone (>40 m). The tectonic setting in Limestone Gap is very complicated, with several E-W striking strike-slip faults and N-S striking reverse/thrust faults with west-directed shortening. Several reverse faults cut the Nelchina-Bedlamite-Garstone unit and form duplex structures. At the fossil location, a reverse fault places Nelchina Limestone onto the calcareous mudstone, effectively wedging it between the strong limestone. It is very likely that the relative weak mudstone accommodates much of the strain by means of internal deformation.

The mudstone, though apparently soft at the weathering surface, is competent to enough to prevent complete strain partitioning between matrix and belemnite rostrum. In other words, the belemnites are sufficiently attached to the matrix to respond to the strain forced upon the mudstone. Thus, the deformed belemnites can serve as strain indicators.

What useful information can be extracted from deformed belemnites that we don't already know?

Conditions in other areas might not be favourable enough to preserve regional structural features as in south central Alaska. Belemnites are very resistant to weathering. In such cases, sheared and bent belemnite rostra might be the only indicators of compressive tectonic stress. In order to validate this conclusion, more contractionally deformed belemnites need to be discovered. However, in Alaska we can exclude an impact of an extraterrestrial body as the origin of sheared belemnites!

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Acknowledgments:
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