

Influence of Anisotropy in Sediment Mechanical Properties on CH₄ Bubble Growth Topology and Migration Pattern in Muddy Aquatic Sediments

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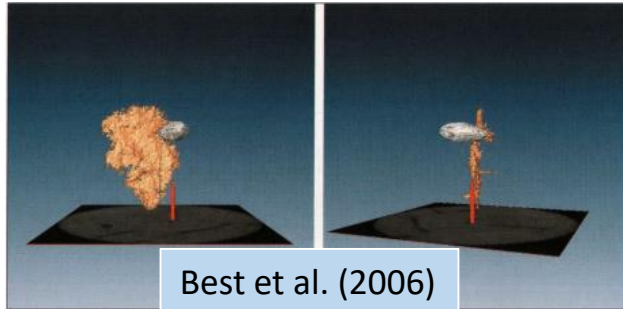
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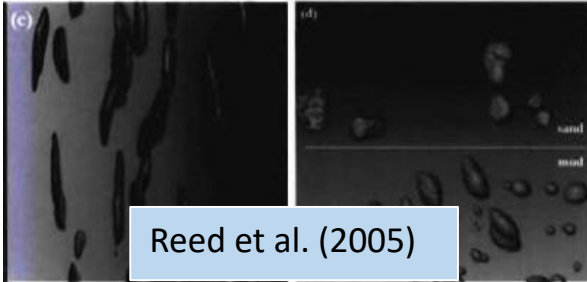
Bubbles in Fine-Grained Muddy Aquatic Sediments

- Discrete methane bubbles are abundantly found in muddy aquatic sediments, resulting from microbial degradation of organic matter and are a significant source of atmospheric methane.
- Recent 3D-CT images of bubbles in their in-situ stress conditions, reports a controversial observation in their orientation. Bubbles are observed to have alignment in **vertical** (Best et al., 2006; Reed et al., 2005; Boudreau et al., 2005) as well as in **horizontal** direction (Johnson et al., 2017; Blouin et al., 2019; Liu et al., 2018).

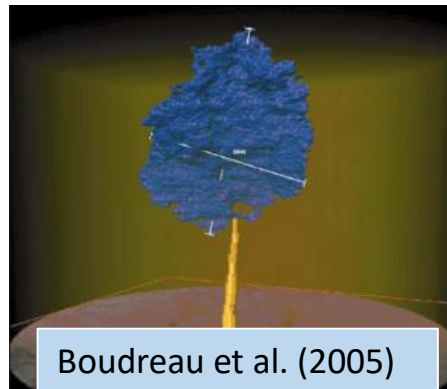
Images of Vertical Oriented Bubbles



Best et al. (2006)



Reed et al. (2005)



Boudreau et al. (2005)

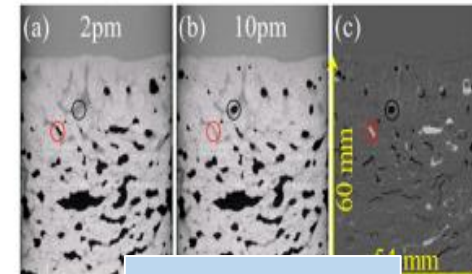
Images of Horizontal Oriented Bubbles



Johnson et al. (2017)



Blouin et al. (2019)



Liu et al. (2018)

Preferred Orientation of Bubbles in Muds

- Muds are characterized with small pore throat radii (dominated by clay- and silt-sized particles, $<63\text{ }\mu\text{m}$), resulting in high capillary-entry pressure. This preclude gas from intruding adjacent pores without breaking inter-particle cohesive and adhesive bonds, and thus favors bubble growth by fracture-dominated mechanism (Jain and Juanes, 2009).
- Muds responds mechanically as linear elastic fracturing material to growing bubbles; incubating thin oblate spheroid (or disk) like bubbles (Johnson et al., 2002). Classical *maximum tensile stress theory* in Linear elastic fracture mechanics (LEFM) (Jaeger and Cook, 1976) asserts that material fails when least principal stress (associated with maximal tension (negative)) reaches fracture tensile strength of material, and fracture propagates along the plane orthogonal to least principal stress. In sediments under influence of vertical overburden load, minimum compressive stress is horizontal one. Thus, bubbles formed in muds orient them self vertically. Similar vertical structures are observed while rise of magma filled dykes and pressurized fluids in glaciers (Dahm, 2000).
- However, no established theory adequately explains the horizontal growth of bubbles in muds.

Research Questions?

- What factors control the growth orientation (**Horizontal** vs. **Vertical**) of bubbles in muds?
- What are implications of bubble growth orientation for gas release mechanism from muds, and for formation of gas bubble networks within sediments?

Objectives:

- Present study is aimed to explore an effect of anisotropy in fracture toughness (a material property quantifying the sediment's crack resisting ability) of muddy sediment on bubble growth direction.

Methods

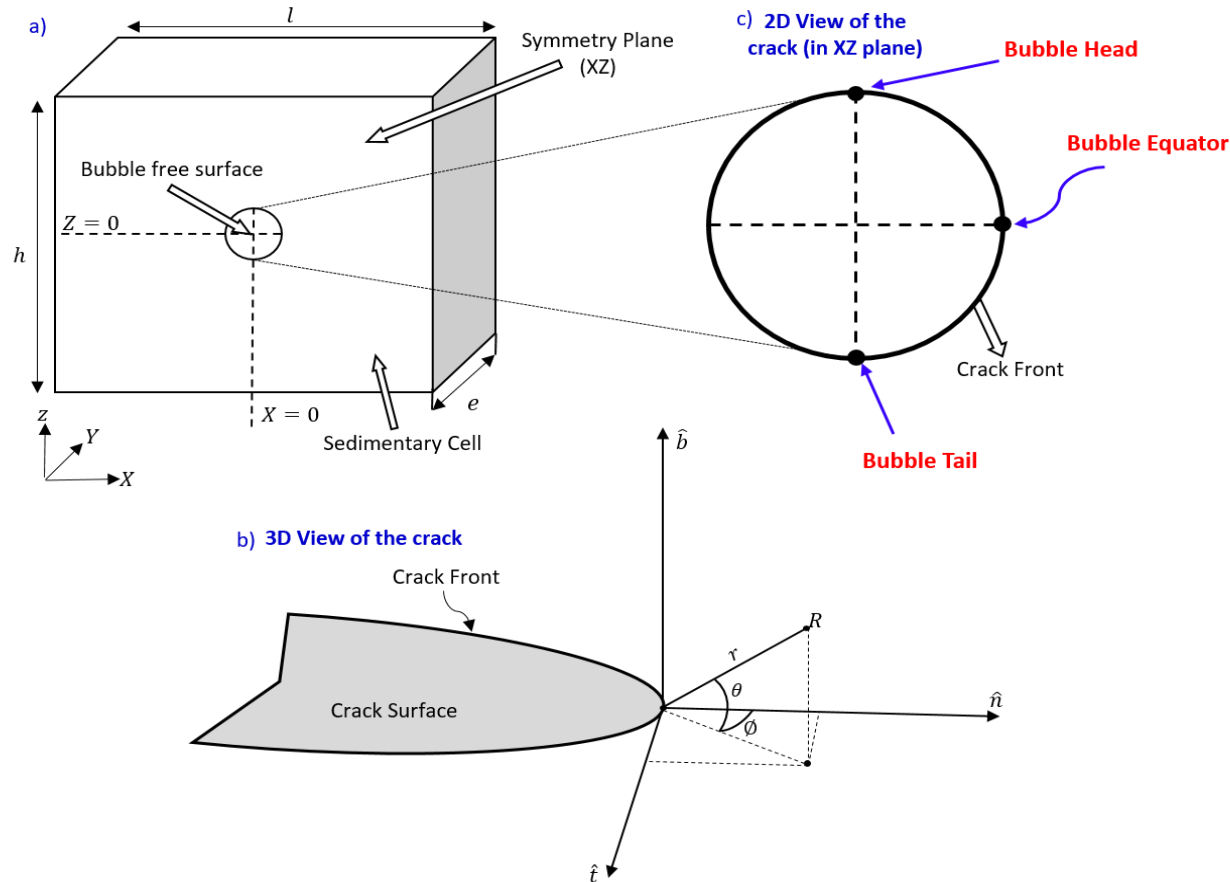


Figure 1. Schematic of modelling setup: a) A 3D sediment domain sliced by a symmetry plane, enclosing a penny-shaped bubble with one of its surfaces coincident with symmetry plane; b) 3D view of penny-shaped crack periphery with local boundary coordinate system $(\hat{t}, \hat{n}, \hat{b})$ and local spherical co-ordinate system (r, θ, ϕ) ; c) 2D in-plane view of penny-shaped crack.

- Present work simulates the growth process of a CH₄ bubble in a fine-grained aquatic sediment, exhibiting an inherent anisotropy in Mode I fracture toughness (K_{IC}), while assuming elastic response of sediment as isotropic.
- We employed a mechanical reaction-transport model, developed in Katsman et al. (2013), which couples the processes of CH₄(g) gas bubble expansion diffusion-fed from the surrounding field of CH₄(aq) dissolved in pore waters, with elastic-fracture (LEFM) mechanical response of sediment to the growing bubble.

Methods (Contd.)

- Solute conservation for dissolved methane, to model the diffusive transport within elementary sediment domain to growing bubble is modeled as :

$$\frac{\partial(C_{CH_4}(g)V_b)}{\partial t} = \int_{\alpha} \vec{n} \cdot (-D\phi \nabla C_{CH_4}(aq)) d\alpha$$

where $C_{CH_4}(aq)$ is aqueous methane concentration, D is tortuosity-corrected diffusion coefficient of methane in bulk sediment and t is time.

- Conservation of gaseous methane for growing bubble is modeled here by the equation:

$$\frac{\partial(C_{CH_4}(g)V_b)}{\partial t} = \int_{\alpha} \vec{n} \cdot (-D\phi \nabla C_{CH_4}(aq)) d\alpha$$

where $C_{CH_4}(g)$ is methane gas concentration at bubble surface, V_b is bubble volume, $\vec{n}$ is normal to bubble surface α and $\frac{C_{CH_4}(g)}{C_{CH_4}(aq)}$ is porosity.

- The linear elastic mechanical response of sediment domain to bubble expansion and to gravity load ($\vec{F}_g$) is simulated as, $-\nabla \cdot \sigma = \vec{F}_g$, where σ is Cauchy stress tensor.
- Methane concentration over bubble surface is simulated according to Henry Law.
- When fracturing condition is satisfied at bubble front, bubble grow by propagating its front in agreement with LEFM.

Crack Propagation in Anisotropic sediments

- Anisotropic sediments exhibit direction dependent mechanical strength, which are quantified here with critical *Strain energy density factor* (S_{cr}), an intrinsic material parameter quantifying the materials ability to resist crack initiation and propagation.
- Present work employs a generalized form of *Strain energy density criterion*, to model crack growth in sediment with anisotropic mechanical properties, following Sih and Cha (1974) and Nobile and Carloni (2004). According to this criteria, a material fails when the local strain energy density factor, $S(\theta, \phi)$, acquires its critical value $S_{cr}(\theta, \phi)$, i.e., $S(\theta, \phi) \geq S_{cr}(\theta, \phi)$, and crack extends along a direction (θ, ϕ) , given by minimizing the ratio:

$$S^*(\theta, \phi) = \frac{S(\theta, \phi)}{S_{cr}(\theta, \phi)}$$

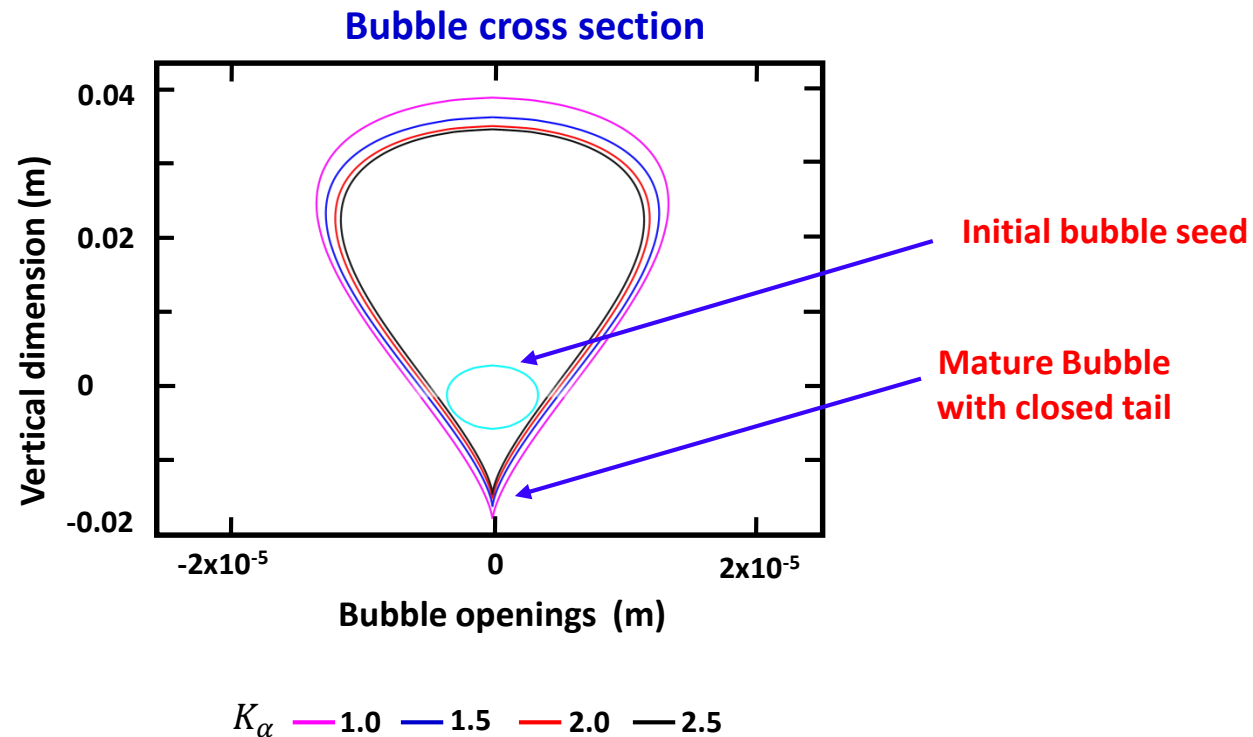
- In crack plane (XZ), we specify direction dependent critical *Strain energy density* as

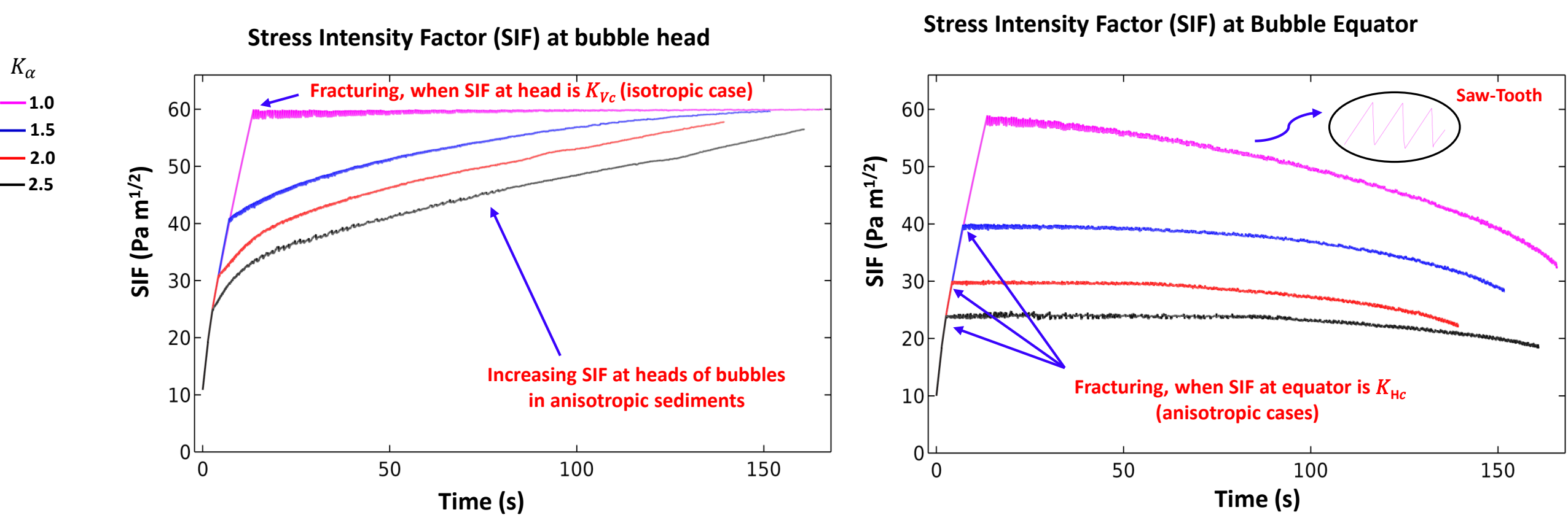
$$S_{cr}(\hat{P}) = S_{cr}^x + (S_{cr}^z - S_{cr}^x) \cdot f(\delta, \phi)$$

where S_{cr}^x and S_{cr}^z are critical *Strain energy density* in horizontal and vertical direction respectively. Dimensionless quantity $f(\delta, \phi)$ takes value 0, 1 in horizontal and vertical direction, where δ is angle between normal to crack front with X-axis.

Results

Bubble growth is simulated in anisotropic sediments – having contrast in values of Mode I fracture toughness in vertical (K_{Vc}) and in horizontal (K_{Hc}) directions. Four cases are presented here, characterized by $K_\alpha = K_{Vc}/K_{Hc} = 1, 1.5, 2, 2.5$ and K_{Vc} is fixed at $60 \text{ Pa m}^{1/2}$. Case $K_\alpha = 1$ corresponds to isotropic sediments. Simulation are initiated from initial bubble seed till the bubbles close their tails, thus reaching their mature configurations.

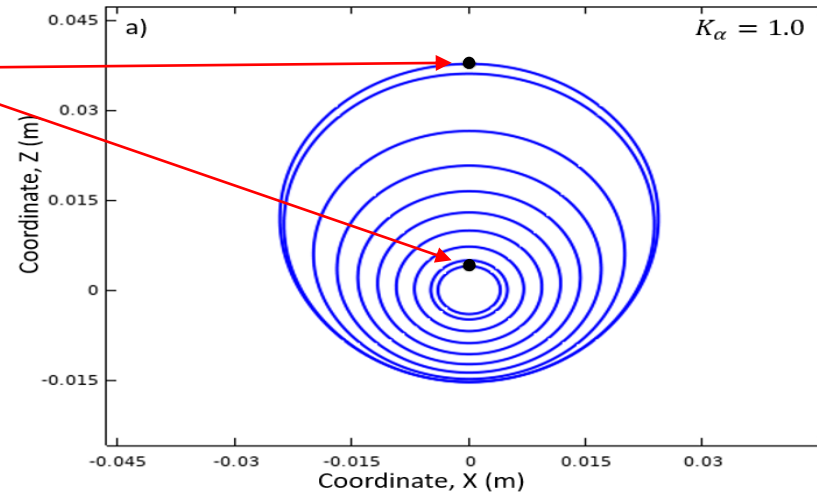
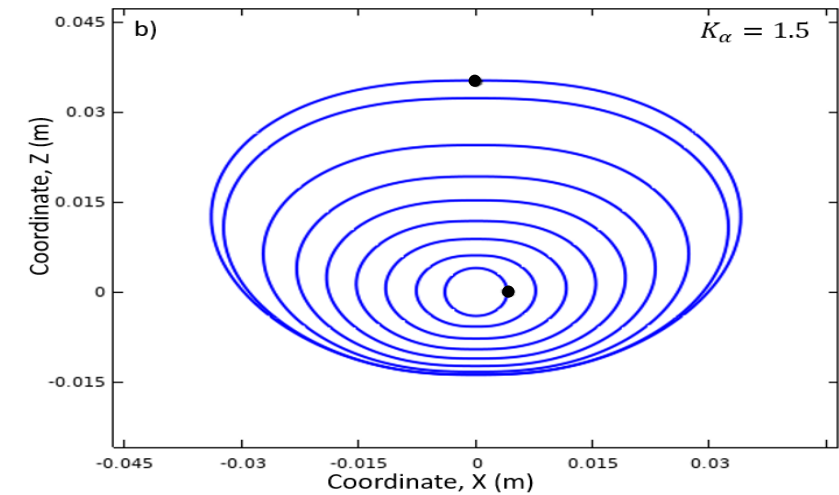




- Bubbles in isotropic sediments initiate fractures, when Stress Intensity Factor (SIF) at head reaches critical value of fracture toughness (K_{Vc}) in vertical direction. Thus, initiating fracturing at bubble head. In contrast, bubbles in anisotropic sediments initiate fractures, when SIF at equator attain critical fracture toughness (K_{Hc}) in horizontal direction (due high anisotropy). Thus, initially these bubbles initiate fractures at bubble equator. However, with bubble growth, the fracture initiation point migrates towards head, leading to increase in SIF at bubble head.
- At fracturing event, bubble experiences instantaneous increase in volume and decrease in internal pressure. Thus, SIF drops simultaneously at fracturing events, followed by its gradual rise due to continuous pressure built-up caused by solute supply (creating a saw tooth pattern).

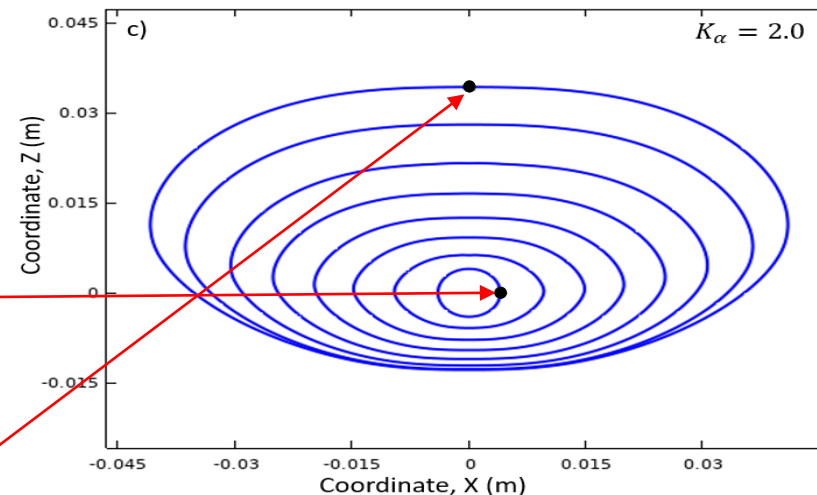
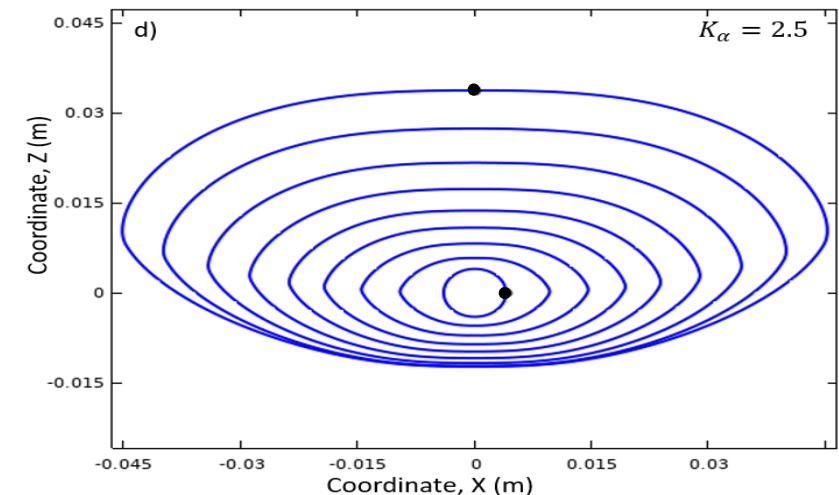
Evolution of bubble front from initial ($t = 0$ s) to their mature (at $t = 165.5$ s, 151.5 s, 139.5 s, 160.8 s in $K_\alpha = 1, 1.5, 2.0, 2.5$, respectively) configurations, in time intervals of 20 s. Black circles over bubble front, represents the position of crack initiation.

In isotropic sediments ($K_\alpha = 1$), fracture initiation point always lies at bubble head



In anisotropic sediments ($K_\alpha > 1$):

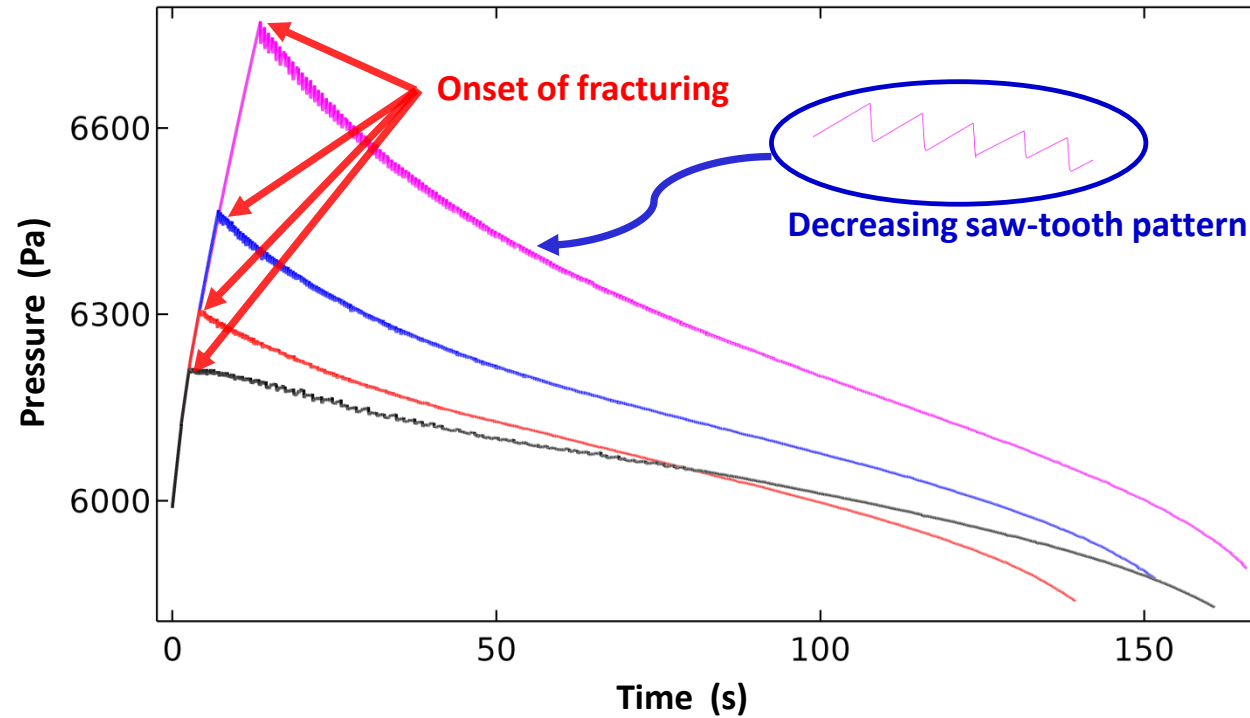
- Initially fracture initiation point lies at bubble equator.
- Fracture initiation point migrate towards bubble head as it matures



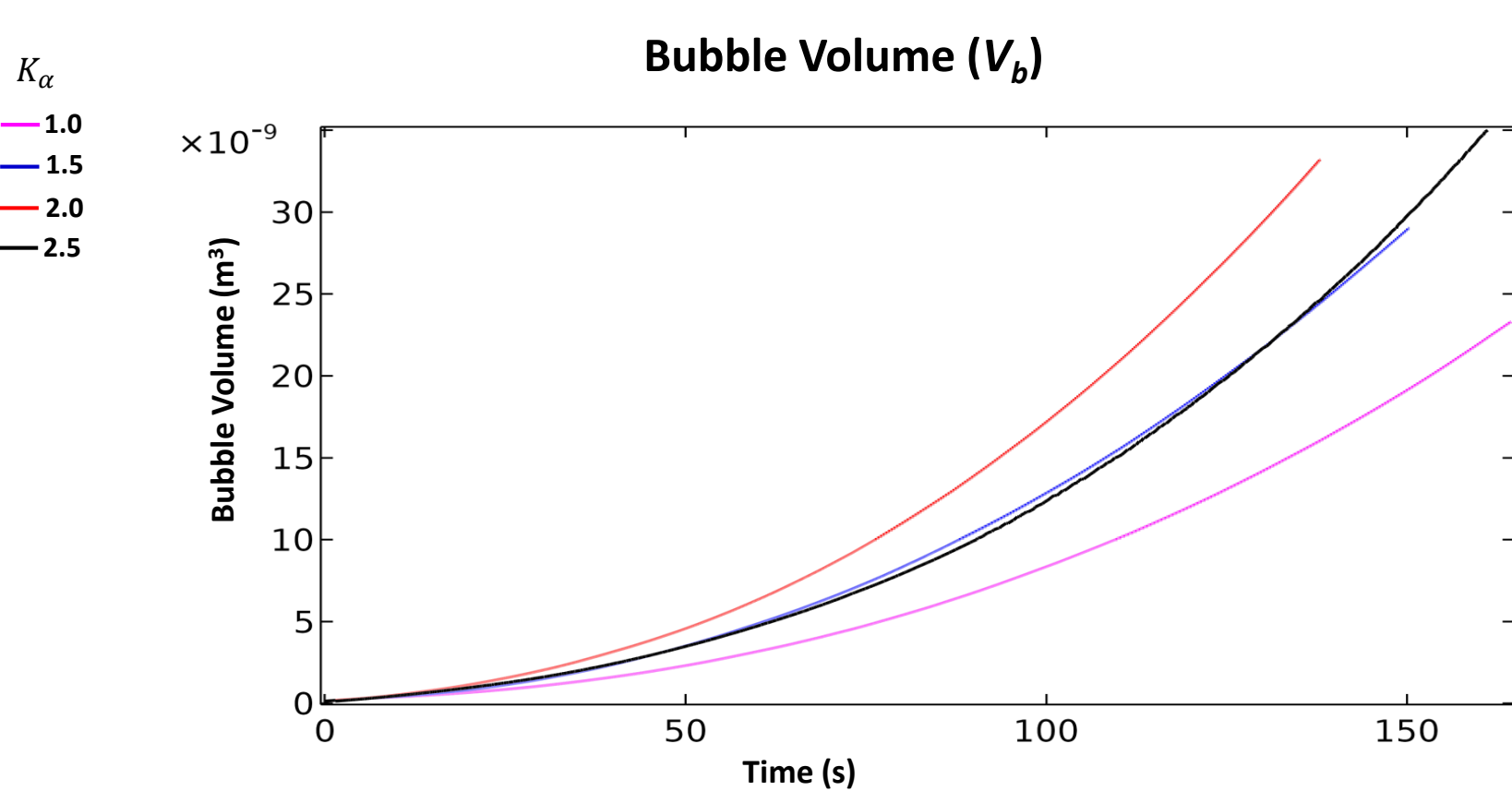
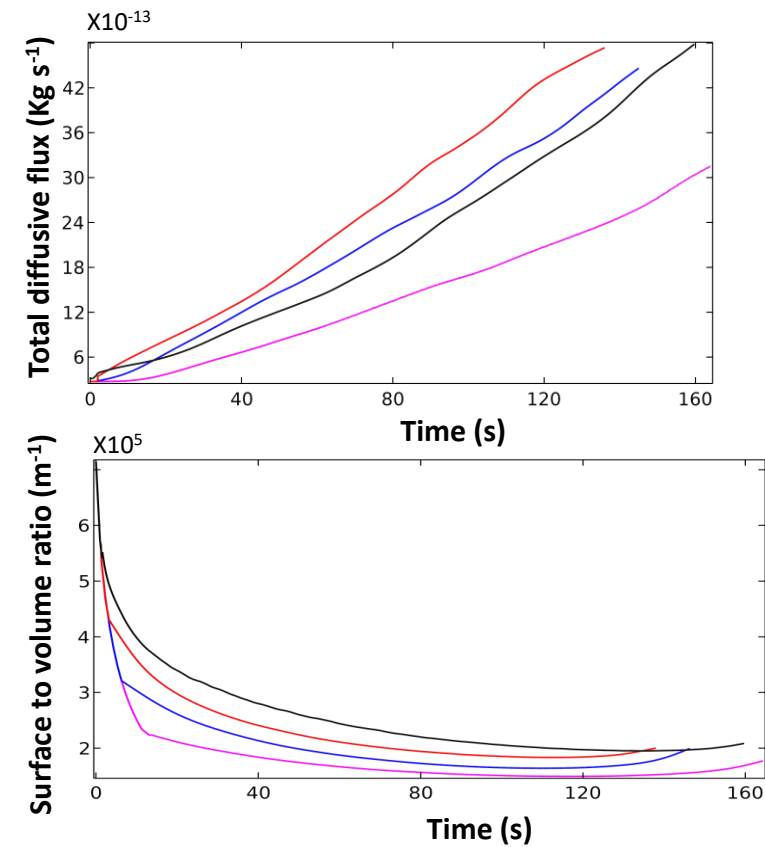
Inner Pressure of Bubbles (P_b)

K_α

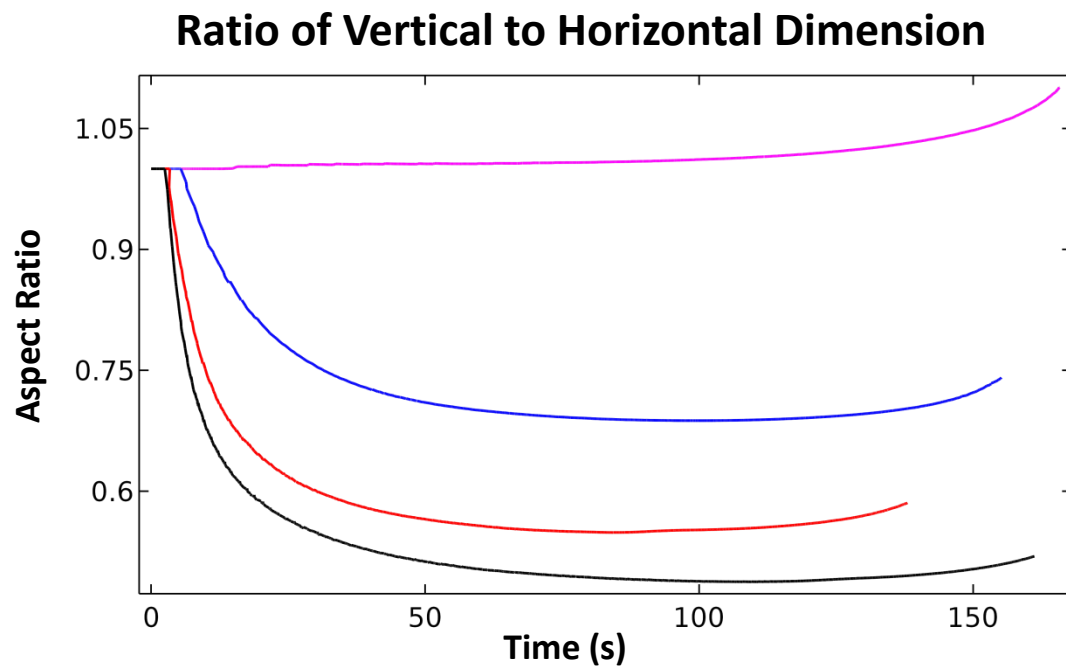
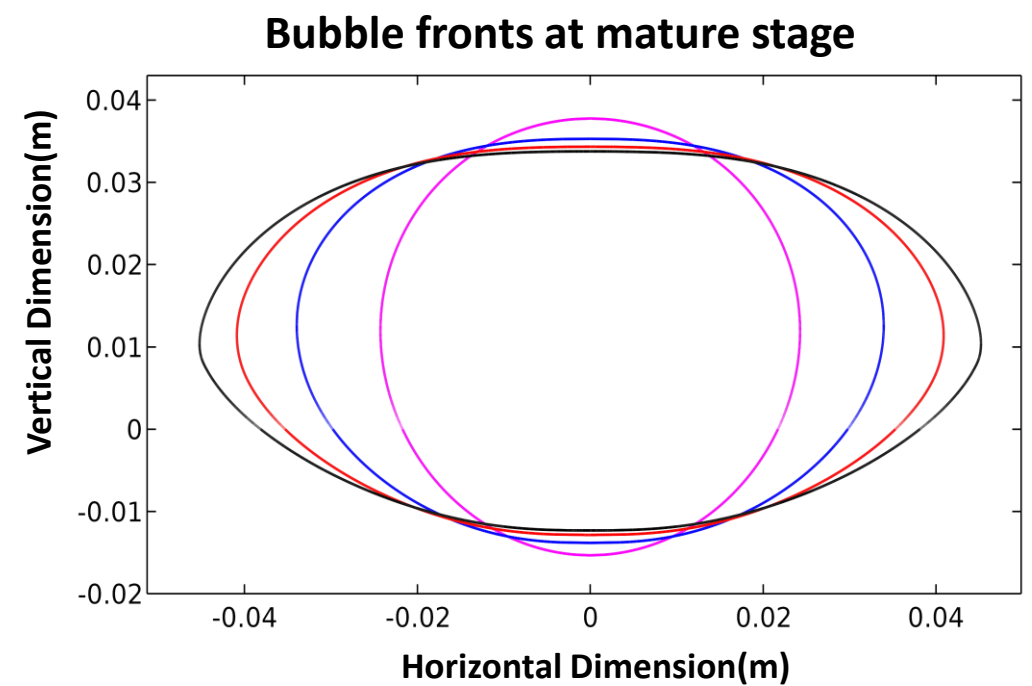
1.0
1.5
2.0
2.5



- Bubbles in anisotropic sediments initiated fractures at lower SIF, therefore their internal pressure at onset of fracturing, decreases with increasing anisotropy.
- Bubbles in sediments experience local compressive stress, σ_y , normal to its surface. Due to gravity, σ_y increase linearly with depth, which inherently determine the SIF gained at given internal pressure. Therefore, as bubbles gain height, they experience relative lower σ_y at their head, equator. This enable bubbles to attain critical SIFs at lower P_b , hence pressure profiles decline temporally.



- Bubbles in anisotropic sediments ($K_\alpha > 1$) grow fast as compared to bubble in isotropic sediment ($K_\alpha = 1$). This is because the bubbles in anisotropic sediments grow at higher surface to volume ratio. This enhances their sensitivity to the ambient solution field and accelerate their growth rate.
- However, bubble in $K_\alpha = 2.5$ grew relatively slower among bubbles in anisotropic sediments, due to its lower total diffusive flux. This bubble grows preferably in horizontal direction, preserving its higher inner pressure, at later growth period ($t > 80$ s), when P_b in other bubbles drops significantly. A higher concentration at bubble surface (due to higher P_b) along with depleted ambient CH_4 concentrations around the preserved deeper bubble position, leads to smaller bubble solute influx, thus slowing bubble growth.



- Attributed to fracturing at head, bubble in isotropic case grows vertically with aspect ratio greater than unity.
- In anisotropic sediment, initial fracturing at equator leads to growth of horizontal dimension of bubbles. Therefore, their aspect ratio decreases rapidly. However, as the fracture initiation point approaches bubble head, they grow in vertical direction as well, so aspect ratio rises as well. At mature stage bubbles in anisotropic sediments exhibit horizontal orientation with aspect ratio lower than unity.
- Increasing anisotropy leads to increase in horizontal dimension of bubbles with comparatively less vertical height.

Discussion

- In absence of enough solute, a bubble with horizontal orientation in anisotropic sediment may become arrested before reaching its mature height, preventing its ascent. This explains the large number of discrete laterally oriented gas bubbles observed in recent lab experiments (Johnson et al., 2017; Blouin et al., 2019; Liu et al., 2016).
- Laterally growing bubbles have ability of coalesce with neighboring ones, resulting in formation of interconnected permeable low-tortuous gas network, transporting gas content to larger distances (Johnson et al., 2017; 2018).
- Continuous solute supply enable bubbles to liberate by developing interconnected macrospores or networks (Johnson et al., 2018; Liu et al., 2018), while having roots in formerly elongated configuration or in lateral network of coalesced bubbles.

Discussion (contd.)

- Gas bubbles in sediments often liberate via spatially distributed small and large scale venting outlets (Scandella et al., 2017; Judd and Hovland, 2009); proposed to accumulate their gas pool via diffusive mass transport. Our study asserts that anisotropy can lead to development of horizontal oriented cavities, amplifying their ability to unite with bubbles in horizontal plane, and thereby transporting gas content up to long distances.
- Recent lab experiments demonstrate high gas storage capacity of sediments (Liu et al., 2018; Blouin et al., 2019) compared to much smaller in-situ gas content of natural sediments (Nageswaran, 1983). This is mainly due to observed horizontal bubble growth (which tend to be stationary) and due to enhanced anisotropy of sediments under low overburden load.

Acknowledgements

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References

- Best, A. I., Richardson, M. D., Boudreau, B. P., et al. (2006). Shallow seabed methane gas could pose coastal hazard. *Eos, Transactions American Geophysical Union*, 87(22), 213-217.
- Blouin, A., Sultan, N., Callot, J.-P., & Imbert, P. (2019). Sediment damage caused by gas exsolution: A key mechanism for mud volcano formation. *Engineering Geology*, 263, 105313.
- Boudreau, B. P., Algar, C., Johnson, B. D., Croudace, I., Reed, A., Furukawa, Y., Dorgan, K. M., Jumars, P. A., Grader, A. S., & Gardiner, B. S. (2005). Bubble growth and rise in soft sediments. *Geology*, 33(6), 517-520.
- Dahm, T. (2000). On the shape and velocity of fluid-filled fractures in the Earth. *Geophysical Journal International*, 142(1), 181-192.
- Jaeger, J. C., & Cook, N. G. W. (1976). *Fundamentals of rock mechanics*, (2nd ed.). London: Chapman and Hall.
- Jain, A. K., & Juanes, R. (2009). Preferential mode of gas invasion in sediments: Grain-scale mechanistic model of coupled multiphase fluid flow and sediment mechanics. *Journal of Geophysical Research*, 114, B08101.
- Johnson, B. D., Boudreau, B. P., Gardiner, B. S., & Maass, R. (2002). Mechanical response of sediments to bubble growth. *Marine Geology*, 187(3-4), 347-363.
- Johnson, M., Fairweather, M., Harbottle, D., Hunter, T. N., Peakall, J., & Biggs, S. (2017). Yield stress dependency on the evolution of bubble populations generated in consolidated soft sediments. *AIChE Journal*, 63(9), 3728-3742.
- Johnson, M., Peakall, J., Jia, X., Fairweather, M., Harbottle, D., Biggs, S., & Hunter, T. N. (2018). Enhanced gas migration through permeable bubble networks within consolidated soft sediments. *AIChE Journal*, 64(11), 4131-4147.
- Judd, A., & Hovland, M. (2009). *Seabed fluid flow: The impact on geology, biology and the marine environment*. Cambridge University Press.
- Katsman, R., Ostrovsky, I., & Makovsky, Y. (2013). Methane bubble growth in fine-grained muddy aquatic sediment: insight from modeling. *Earth and Planetary Science Letters*, 377-378, 336-346.
- Liu, L., Kock, T. D., Wilkinson, J., Cnudde, V., Xiao, S., Buchmann, C., Uteau, D., Peth, S., & Lorke, A. (2018). Methane bubble growth and migration in aquatic sediments observed by X-ray μ CT. *Environmental Science & Technology*, 52(4), 2007-2015.

References (contd.)

- Nageswaran, S. (1983). Effect of gas bubbles on the seabed behavior. Ph.D. Thesis, Oxford University.
- Nobile, L., & Carloni, C. (2004). Crack growth in an orthotropic medium. *Journal of the Chinese Institute of Engineers*, 27(6), 899-905.
- Reed, A. H., Boudreau, B. P., Algar, C., & Furukawa, Y. (2005). Morphology of gas bubbles in mud: A microcomputed tomographic evaluation. *Proceedings of the International Conference "Underwater Acoustic Measurements: Technologies & Results"*, Heraklion, Crete, Greece.
- Scandella, B. P., Delwiche, K., Hemond, H. F., & Juanes, R. (2017). Persistence of bubble outlets in soft, methane-generating sediments. *Journal of Geophysical Research: Biogeosciences*, 122(6), 1298-1320.
- Sih, G. C., & Cha, B. C. K. (1974). A fracture criterion for three-dimensional crack problems. *Engineering fracture mechanics*, 6(4), 699-723.

Thanks for your kind attention.