Supplemental Material

Inclination and heterogeneity of layered geological sequences influence dike-induced ground deformation

Matías Clunes[1], John Browning[1, 2, 3], Carlos Marquardt[1, 3], Jorge Cortez[1], Kyriaki Drymoni[4], and Janine Kavanagh[5]

[1]*Department of Structural and Geotechnical Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile*

[2]*Andean Geothermal Centre of Excellence (CEGA), Universidad de Chile, Santiago, Chile*

[3]*Department of Mining Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile*

[4]*Department of Earth and Environmental Sciences, Università degli Studi di Milano-Bicocca, Milan, Italy*

[5]*School of Environmental Sciences, University of Liverpool, Liverpool, United Kingdom*

EXTENDED NUMERICAL MODEL SETUP

Domain size effect

We concentrate only on the results using the domain size specified in the numerical model setup (20 km wide x 20 km deep) but comparisons with larger domain sizes are given Figures S1 and S2. Whilst the total amounts of absolute surface deformation do alter between models with different sized domains, the changes in deformation with heterogeneity and layer inclination, the focus of this work, remain broadly similar regardless of the domain size.

Dike geometry

The lengths, heights and thicknesses of the modelled dikes are all within reasonable sizes of measured dikes in the upper crust (e.g., Gudmundsson, 2011). We have not chosen dike sizes based on any particular field case, but we have simply taken a pragmatic approach to modelling the dike, crust, and layer sizes by varying within factors or orders of magnitude so as to be able to glimpse relevant contrasts.

Overpressure

In all models we used an overpressure of 5 MPa chosen since this represents a value within the range of host rock tensile strengths which are commonly between around 0.5 to 9 MPa (Amadei and Stephansson, 1997; Gudmundsson, 2011; Gudmundsson, 2020) and so could be reasonably associated with dike emplacement. Since our study is concerned with defining the influence of layer inclination on surface deformation, we do not present results related to changes in magmatic overpressure, doing so would change the absolute surface deformation values but the patterns on deformation and layer influence remains the same.

Young's modulus ratios

In nature differences in stiffness are reflective of mechanically stratified volcanic sequences that host stiff units such as lava flows and intrusive rocks, and compliant units such as ash or poorly welded tuff. Whilst in reality some of the Young's modulus contrasts used in our work may be extreme (Heap et al., 2020), since we are interested in the general deformation behavior, we used combinations between 3 orders of magnitude of Young's modulus values (1, 10 and 100 GPa) to probe the full range of possibilities with the acknowledgement that to be applied to any geological unit of interest the rocks should be analytically tested and represents the order of magnitudes which can be found at layered volcanic edifices, such as stratovolcanoes (Gudmundsson, 2020).

Other parameters

We did not assign mechanical properties to the contacts between the layers and density (2700 kg/m^3) and Poisson's ratio (0.25) (Gudmundsson, 2011) of all layers were the same across all the model runs. We modeled the homogeneous crustal segment with a stiffness of 50 GPa chosen because it is close to the average value used between the stiffer (100 GPa) and the more compliant Young's modulus tested (1 GPa).

Area of the modeled layers

The 2D area of the dipping layers varies in the models as a function of inclination angle. The horizontal layer has an area of 4 km^2 which represents the 1% of the crustal segment modeled, the layer inclined 10° 9.25 km^2 (2.3%), the layer inclined 25° 24.2 km^2 (6.1%) and the layer inclined 45° 49.5 km^2 (12.4%).

EXTENDED RESULTS

We focus only on the results obtained from a dike with 2 km length and its upper tip located a 2 km depth probe the relative influence of the surrounding host rock mechanical properties and layer inclination on the magnitude and extent of surface deformation. Our results show that whilst the magnitude of ground displacement varies with dike length and depth, the general patterns relating to layer heterogeneity and inclination are consistently observed for each dike length and depth modeled, but the extent of the absolute ground displacements is different, as expected (Figures S4-S19). To increase the precision of the model fits of change in vertical and horizontal displacement with layer angle, presented in Figure 4 of the manuscript, we added two additional layer angles, 20° and 30°, so as to generate more data points.

DATASETS

Surface displacements dataset

Vertical and horizontal displacements exported from COMSOL Multiphysics are available in a .rar folder ("displacement_data") containing excel files for each computational domain tested and for the different modelled dike geometries and emplacement depths. Each excel file contains 5 sheets, one for each stiffness ratios tested.

COMSOL Multiphysics files

Five COMSOL Multiphysics 5.4 files (.mph) are available in a .rar folder ("COMSOL_files") containing the different crustal geometries modelled. In these files the user can change the layer stiffness in the "Materials" tab by modifying the Young's modulus value. The dike position and geometry can also be changed by modifying the assigned values in the "Geometry" tab. To display the surface displacement (u_x, u_z) results, the user can press the "Compute" button.

REFERENCES CITED

Amadei, B., and Stephansson, O., 1997, Rock stress and its measurement. (Chapman Hall, New York).

Druitt, T., Edwards, L., Mellors, R., Pyle, D., Sparks, R., Lanphere, M., Davis, M., and Barriero, B., 1999, Santorini Volcano. Geological Society Memoir 19:165.

Gudmundsson, A., 2011, Rock fractures in geological processes. Cambridge University Press. 578.

Gudmundsson, A., 2020, Volcanotectonics: Understanding the Structure, Deformation and Dynamics of Volcanoes. Cambridge: Cambridge University Press. doi:10.1017/9781139176217.

Heap, M.J., Villeneuve, M., Albino, F., Farquharson, J.I., Brothelande, E., Amelung, F., Got, J.L., and Baud, P., 2020, Towards more realistic values of elastic moduli for volcano modelling. Journal of Volcanology and Geothermal Research, 390, p.106684.

Nyström, J. O., Vergara, M., Morata, D., & Levi, B., 2003, Tertiary volcanism during extension in the Andean foothills of central Chile (33 15′–33 45′ S). *Geological Society of America Bulletin*, *115*(12), 1523-1537.

Figure S1: Comparison of vertical ground displacement (u_z) variations in percentage relative to the lateral distance from the dike tip obtained from A) domain size of 20 km wide and 20 km deep and B) domain size of 40 km wide and 40 km deep. The displacements are normalised to the domain length (L).

Figure S2: Comparison of horizontal ground displacement variations (u_x) in percentage relative to the lateral distance from the dike tip obtained from A) domain size of 20 km wide and 20 km deep and B) domain size of 40 km wide and 40 km deep. The displacements are normalised to the domain length (L).

Figure S3: A) Simplified geological map from Santorini, Greece, modified from Druitt et al. (1999), where the case study from Figure 1D is located, at the northern caldera wall. B) Simplified geological map from the Andes of Central Chile, near to Santiago, modified from Nyström et al., (2003), where the case study from Figure 1E is located, at an outcrop of the Miocene volcanic rocks from Farellones Formation.

Figure S4: Vertical ground displacement (u_z) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 1 km in length and its upper tip is located at a depth of 1 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.

Figure S5: Vertical ground displacement (u_z) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 2 km in length and its upper tip is located at a depth of 1 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one *material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.*

Figure S6: Vertical ground displacement (u_z) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 4 km in length and its upper tip is located at a depth of 1 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.

Figure S7: Vertical ground displacement (u_z) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 1 km in length and its upper tip is located at a depth of 2 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.

Figure S8: Vertical ground displacement (u_z) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 4 km in length and its upper tip is located at a depth of 2 km. The line colors *indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.*

Figure S9: Vertical ground displacement (u_z) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 1 km in length and its upper tip is located at a depth of 4 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.

Figure S10: Vertical ground displacement (u_z) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 2 km in length and its upper tip is located at a depth of 4 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.

Figure S11: Vertical ground displacement (u_z) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The *modeled dike is 4 km in length and its upper tip is located at a depth of 4 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.*

Figure S12: Horizontal ground displacement (u_x) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 1 km in length and its upper tip is located at a depth of 1 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.

Figure S13: Horizontal ground displacement (u_x) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 2 km in length and its upper tip is located at a depth of 1 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.

Figure S14: Horizontal ground displacement (u_x) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 4 km in length and its upper tip is located at a depth of 1 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.

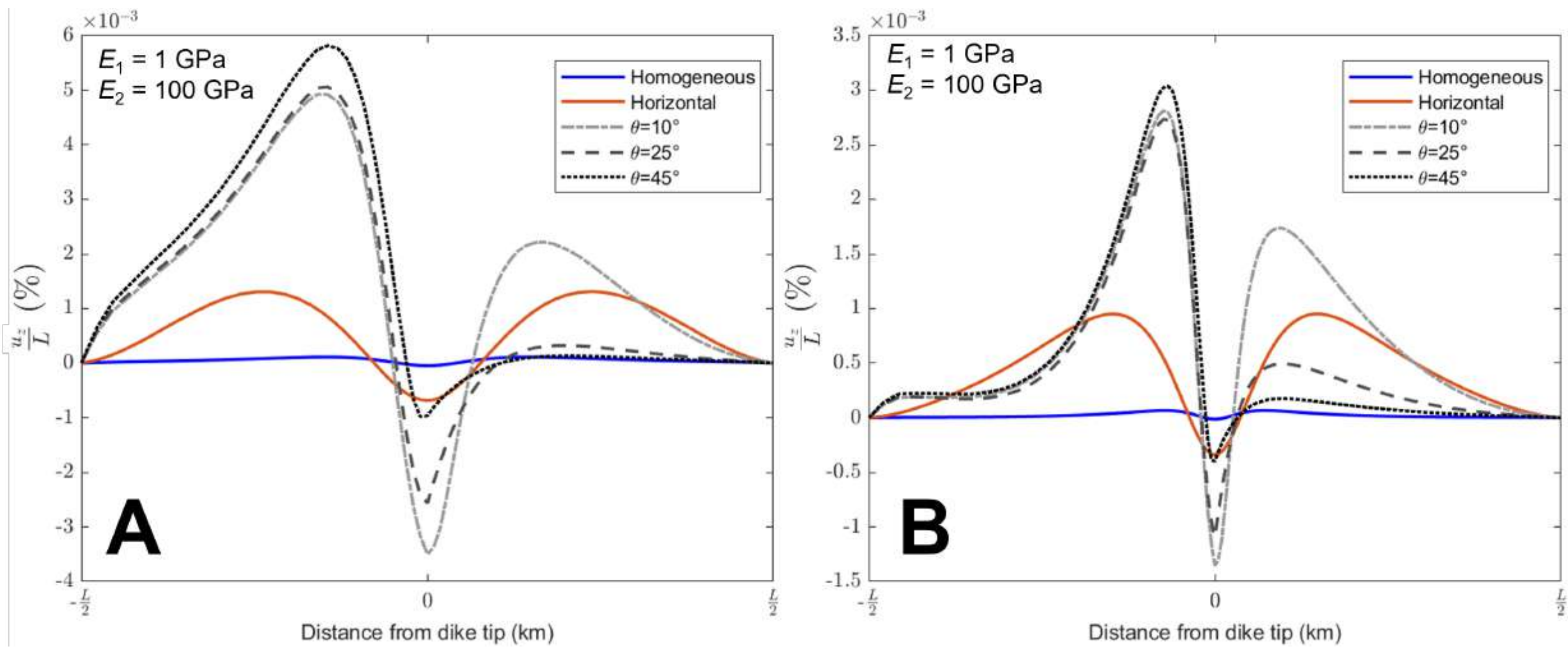
Figure S15: Horizontal ground displacement (u_x) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 1 km in length and its upper tip is located at a depth of 2 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.

Figure S16: Horizontal ground displacement (u_x) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 4 km in length and its upper tip is located at a depth of 2 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.

Figure S17: Horizontal ground displacement (u_x) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 1 km in length and its upper tip is located at a depth of 4 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.

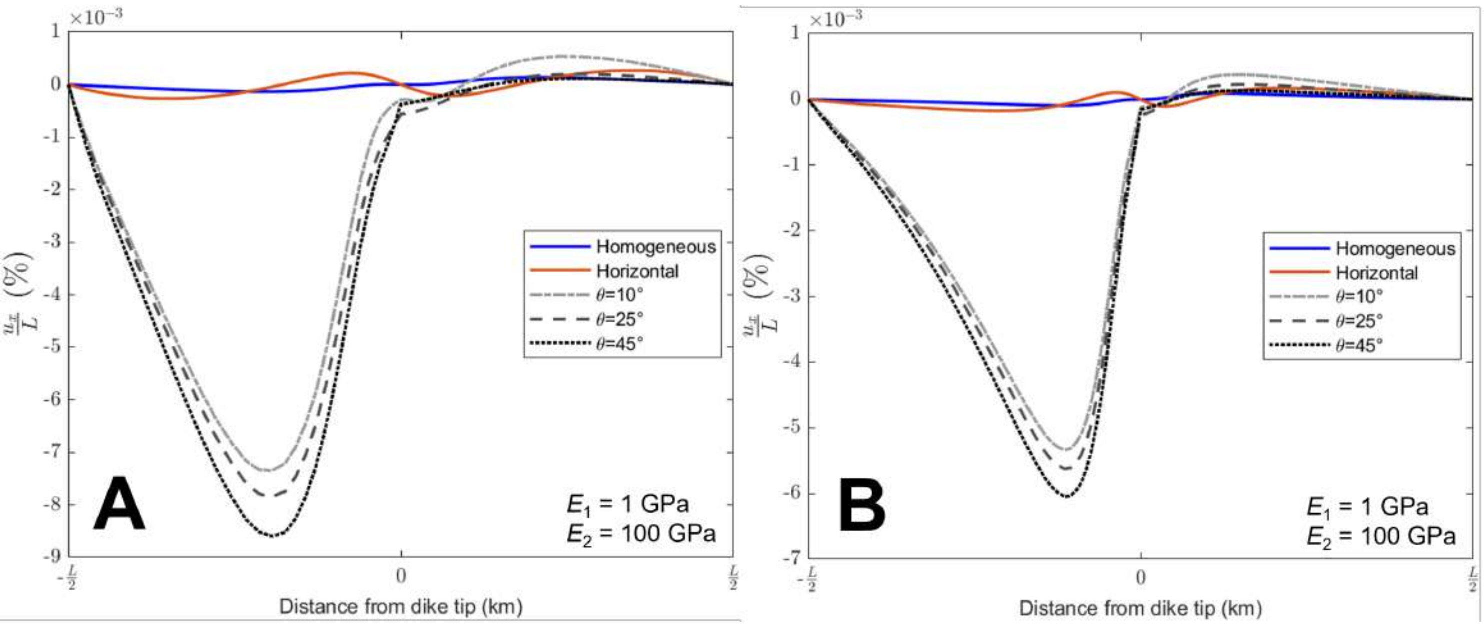
Figure S18: Horizontal ground displacement (u_x) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 2 km in length and its upper tip is located at a depth of 4 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.

Figure S19: Horizontal ground displacement (u_x) variations relative to the lateral distance from the dike tip for each of the modeled layer arrangements and stiffness contrasts tested. The modeled dike is 4 km in length and its upper tip is located at a depth of 4 km. The line colors indicate the geometry of the layers from homogeneous (i.e., where the segment is one material) to horizontal and inclined at 10, 25 and 45 degrees. In A) the stiffness contrast *between the layer hosting the dike (E_1) and the inclined layer (E_2) is 100:1, in B) 1:100, in C) 10:1 and in D) 1:10.*



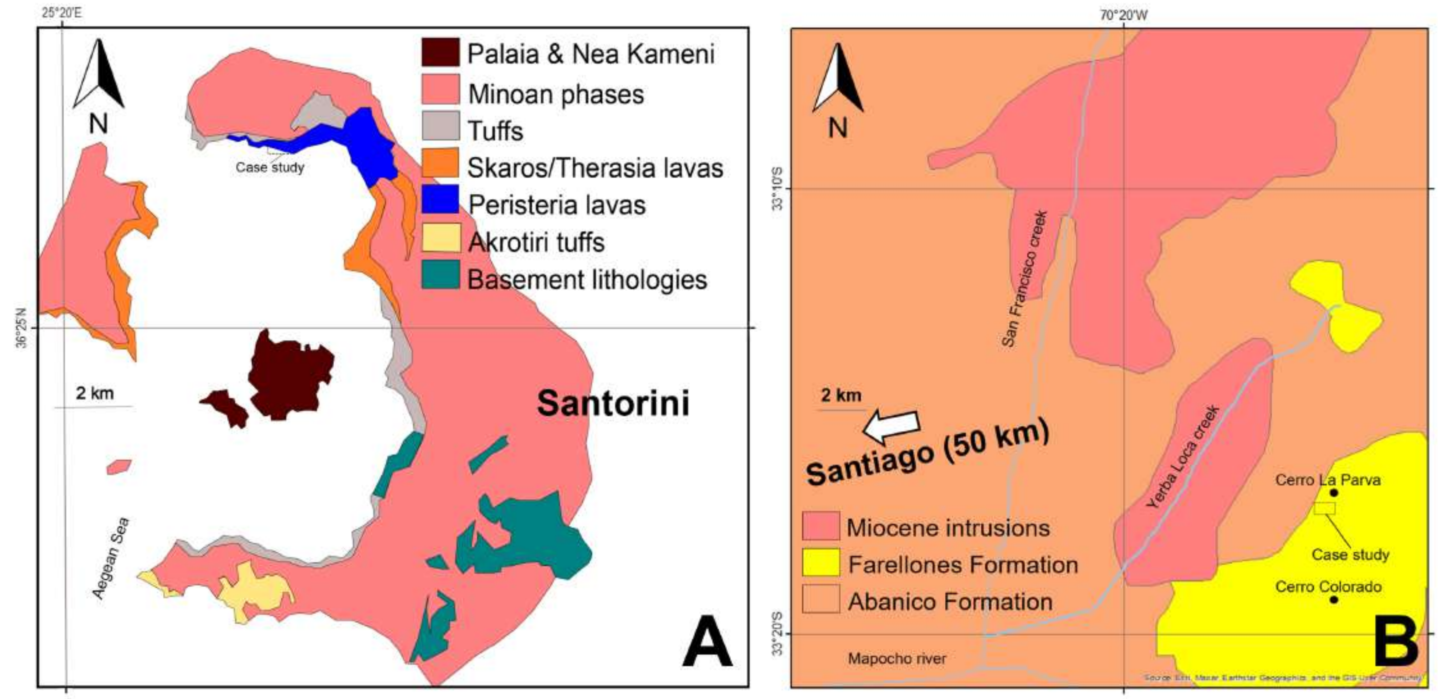
$\times 10^{-3}$
E_1 = 1 GPa
E_2 = 100 GPa
Homogeneous
Horizontal
θ=10°
θ=25°
θ=45°
$\frac{u_z}{L}$ (%)
A
Distance from dike tip (km)
$\times 10^{-3}$
E_1 = 1 GPa
E_2 = 100 GPa
Homogeneous
Horizontal
θ=10°
θ=25°
θ=45°
$\frac{u_z}{L}$ (%)
B
Distance from dike tip (km)

Fig. S1



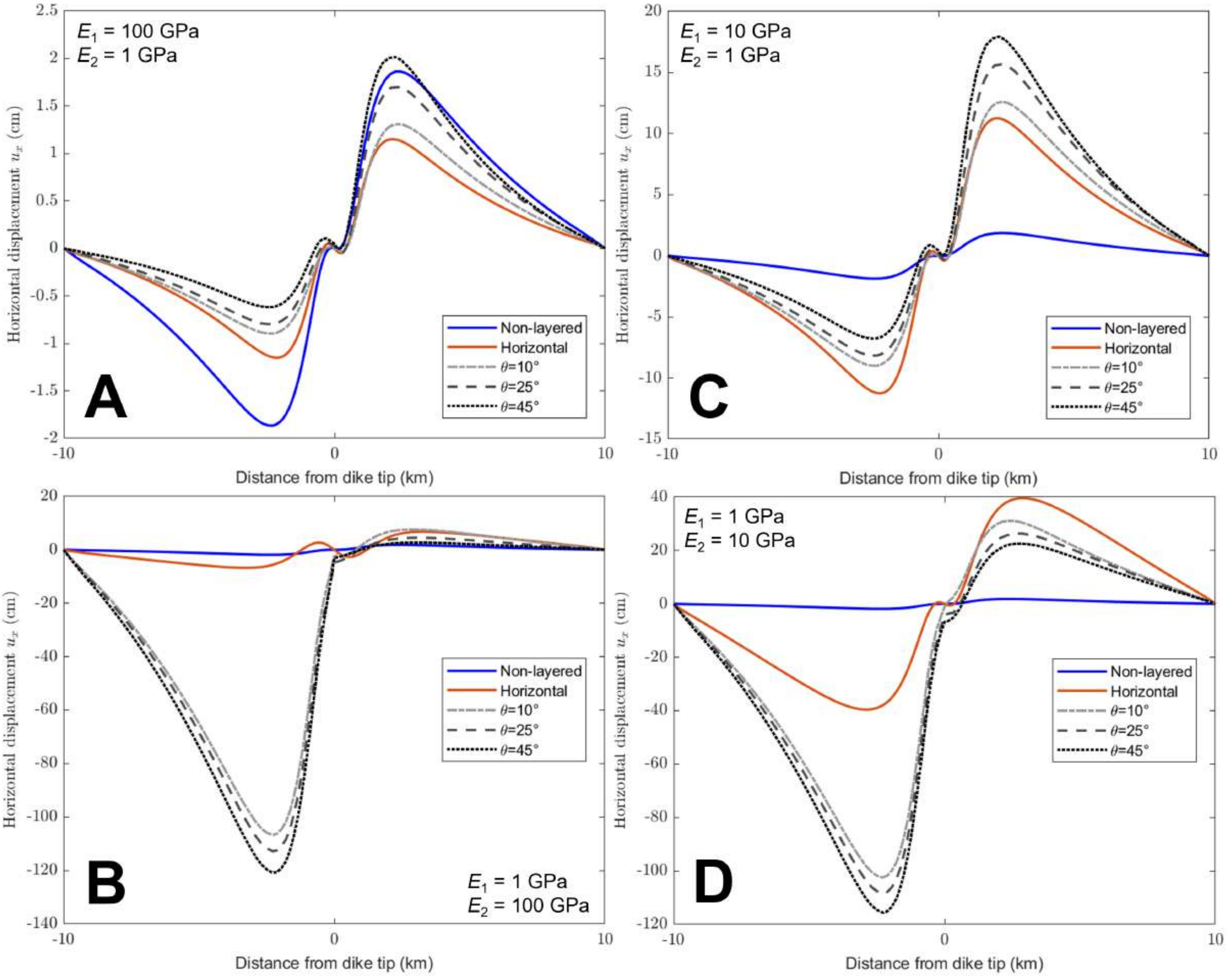
$\times 10^{-3}$
$\frac{u_x}{L}$ (%)
Homogeneous
Horizontal
θ=10°
θ=25°
θ=45°
A
E_1 = 1 GPa
E_2 = 100 GPa
Distance from dike tip (km)
B
E_1 = 1 GPa
E_2 = 100 GPa
Distance from dike tip (km)

Fig. S2



25°20'E
N
Palaia & Nea Kameni
Minoan phases
Tuffs
Skaros/Therasia lavas
Peristeria lavas
Akrotiri tuffs
Basement lithologies
Case study
36°25'N
2 km
Santorini
Aegean Sea
A
70°20'W
N
33°10'S
San Francisco creek
2 km
Santiago (50 km)
Yerba Loca creek
Cerro La Parva
Case study
Cerro Colorado
Miocene intrusions
Farellones Formation
Abanico Formation
33°20'S
Mapocho river
B

Fig. S3



E_1 = 100 GPa
E_2 = 1 GPa
A
E_1 = 10 GPa
E_2 = 1 GPa
C
B
E_1 = 1 GPa
E_2 = 100 GPa
E_1 = 1 GPa
E_2 = 10 GPa
D
Horizontal displacement u_x (cm)
Distance from dike tip (km)
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°

Fig. S4

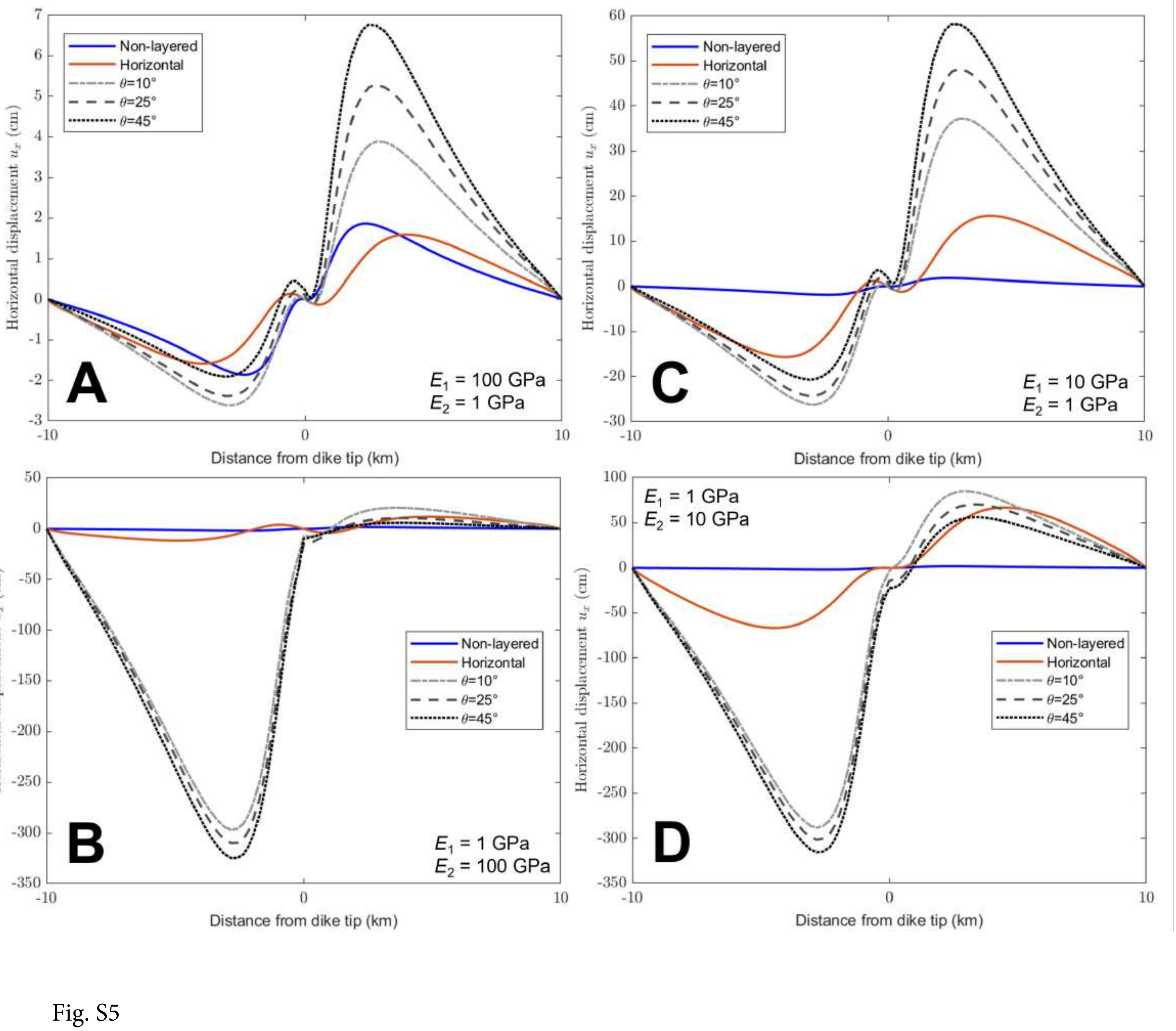
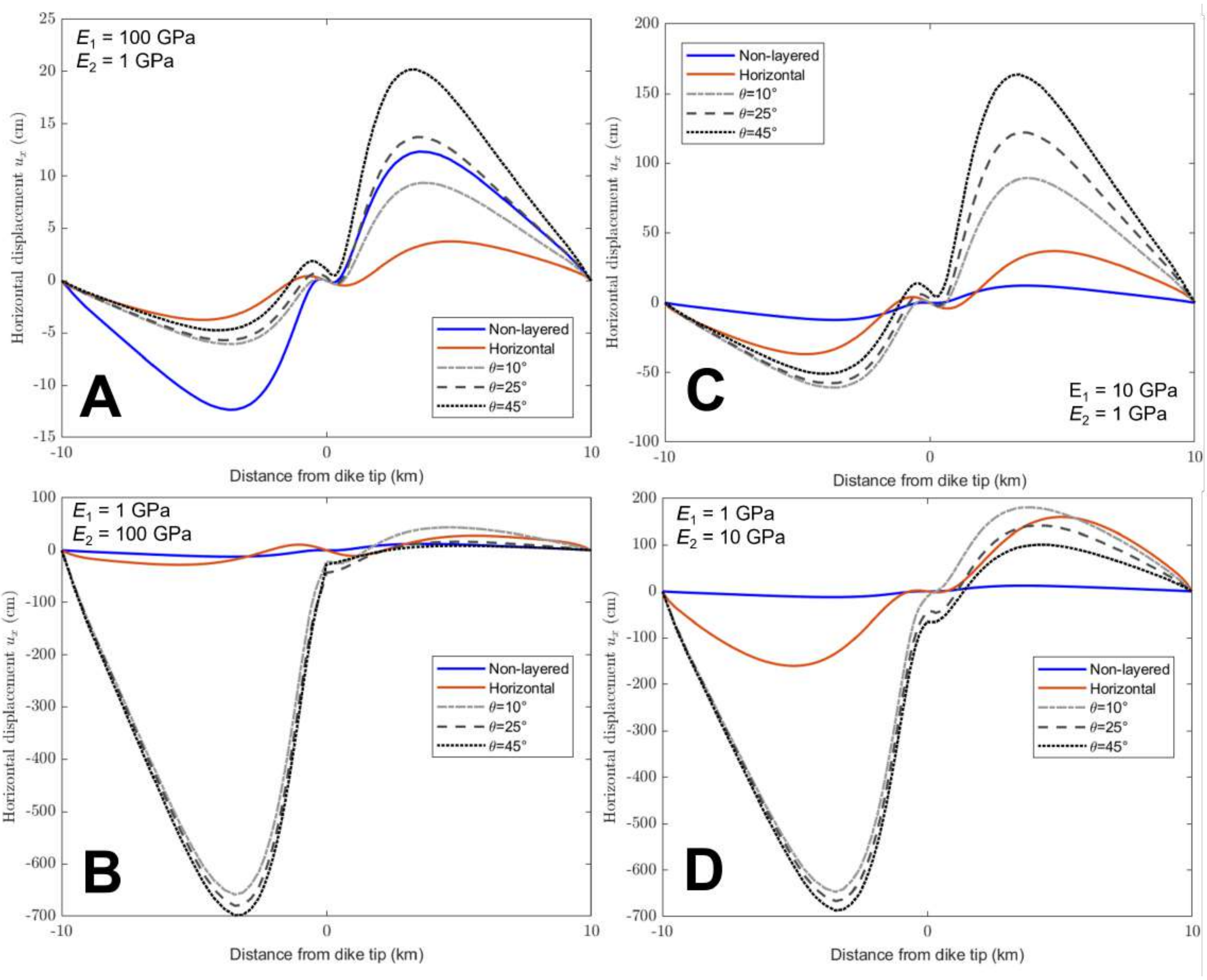
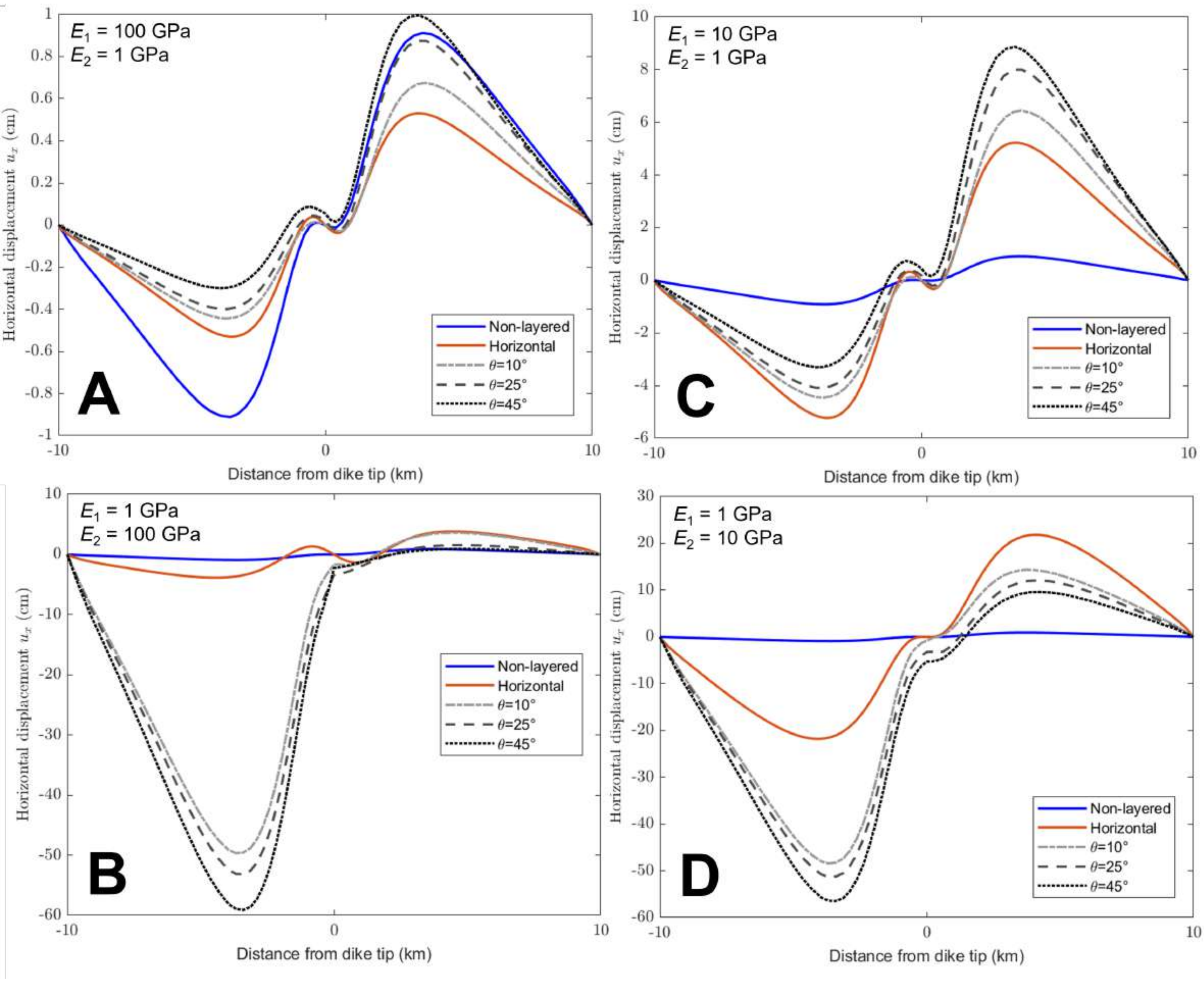

Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
A
E1 = 100 GPa
E2 = 1 GPa
B
E1 = 1 GPa
E2 = 100 GPa
C
E1 = 10 GPa
E2 = 1 GPa
D
E1 = 1 GPa
E2 = 10 GPa
Horizontal displacement ux (cm)
Distance from dike tip (km)

Fig. S5



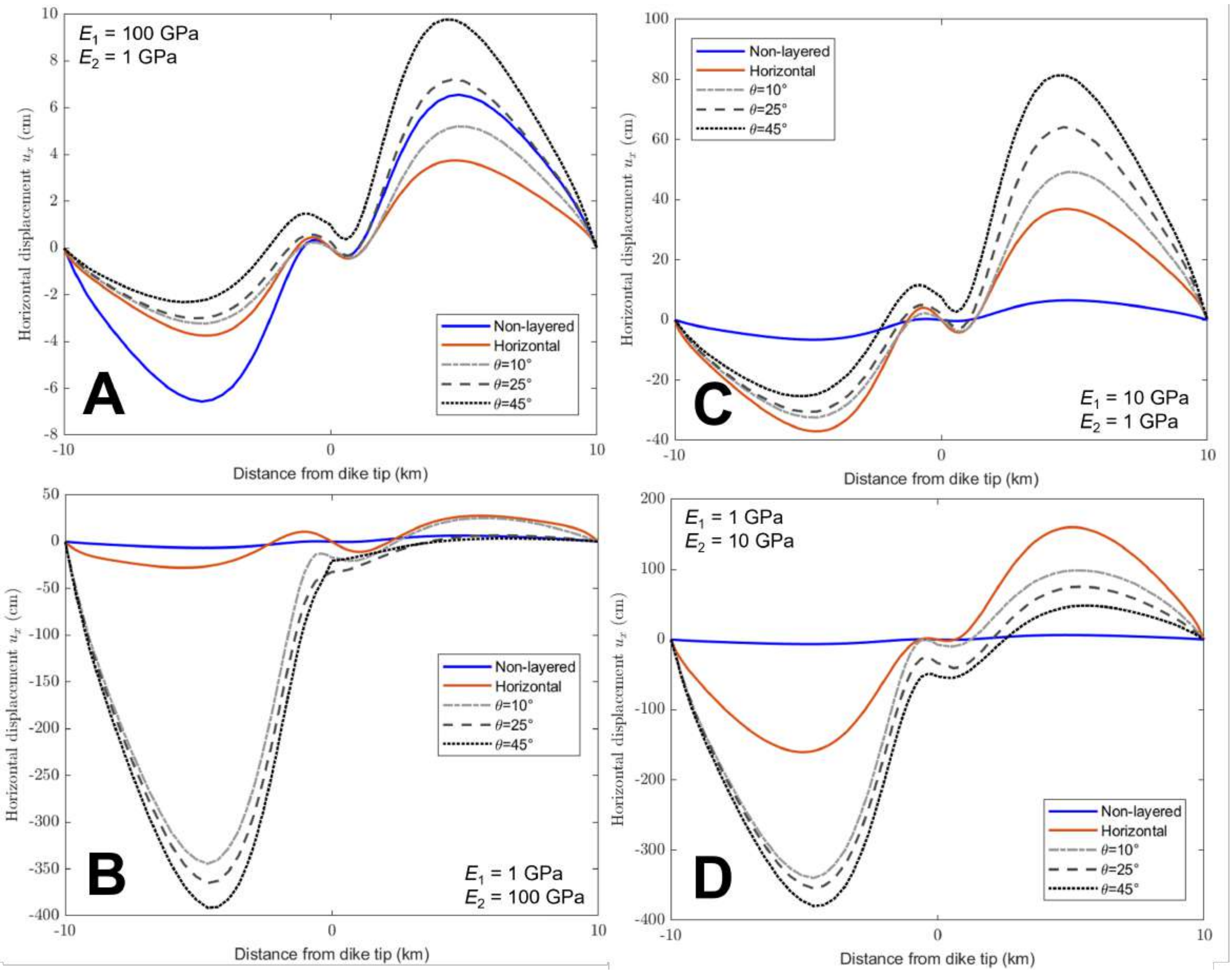
E_1 = 100 GPa
E_2 = 1 GPa
A
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
Horizontal displacement u_x (cm)
Distance from dike tip (km)
C
E_1 = 10 GPa
E_2 = 1 GPa
E_1 = 1 GPa
E_2 = 100 GPa
B
E_1 = 1 GPa
E_2 = 10 GPa
D

Fig. S6



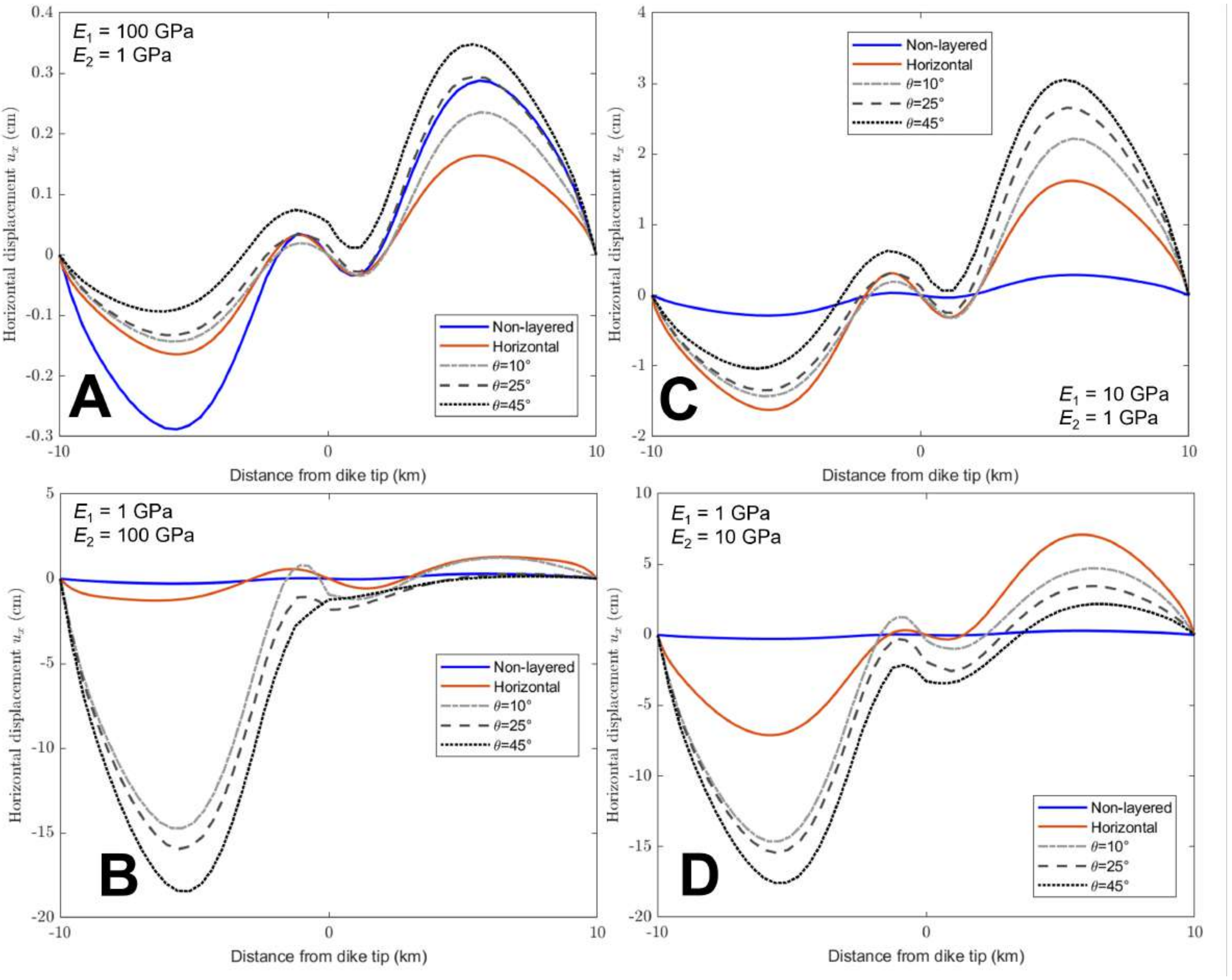
E_1 = 100 GPa
E_2 = 1 GPa
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
A
Horizontal displacement u_x (cm)
Distance from dike tip (km)
E_1 = 10 GPa
E_2 = 1 GPa
C
E_1 = 1 GPa
E_2 = 100 GPa
B
E_1 = 1 GPa
E_2 = 10 GPa
D

Fig. S7



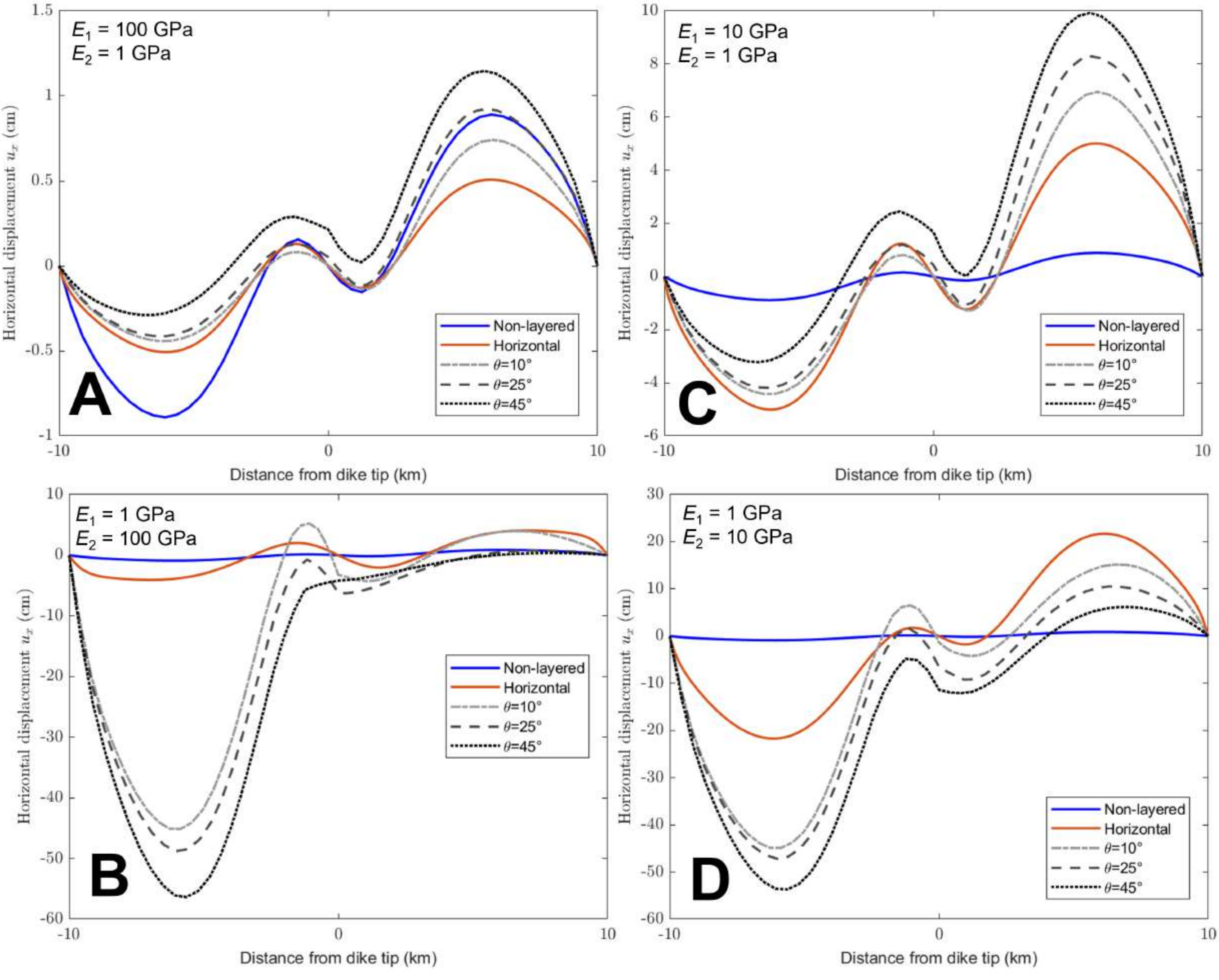
A
E_1 = 100 GPa
E_2 = 1 GPa
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
Horizontal displacement u_x (cm)
Distance from dike tip (km)
B
E_1 = 1 GPa
E_2 = 100 GPa
C
E_1 = 10 GPa
E_2 = 1 GPa
D
E_1 = 1 GPa
E_2 = 10 GPa

Fig. S8



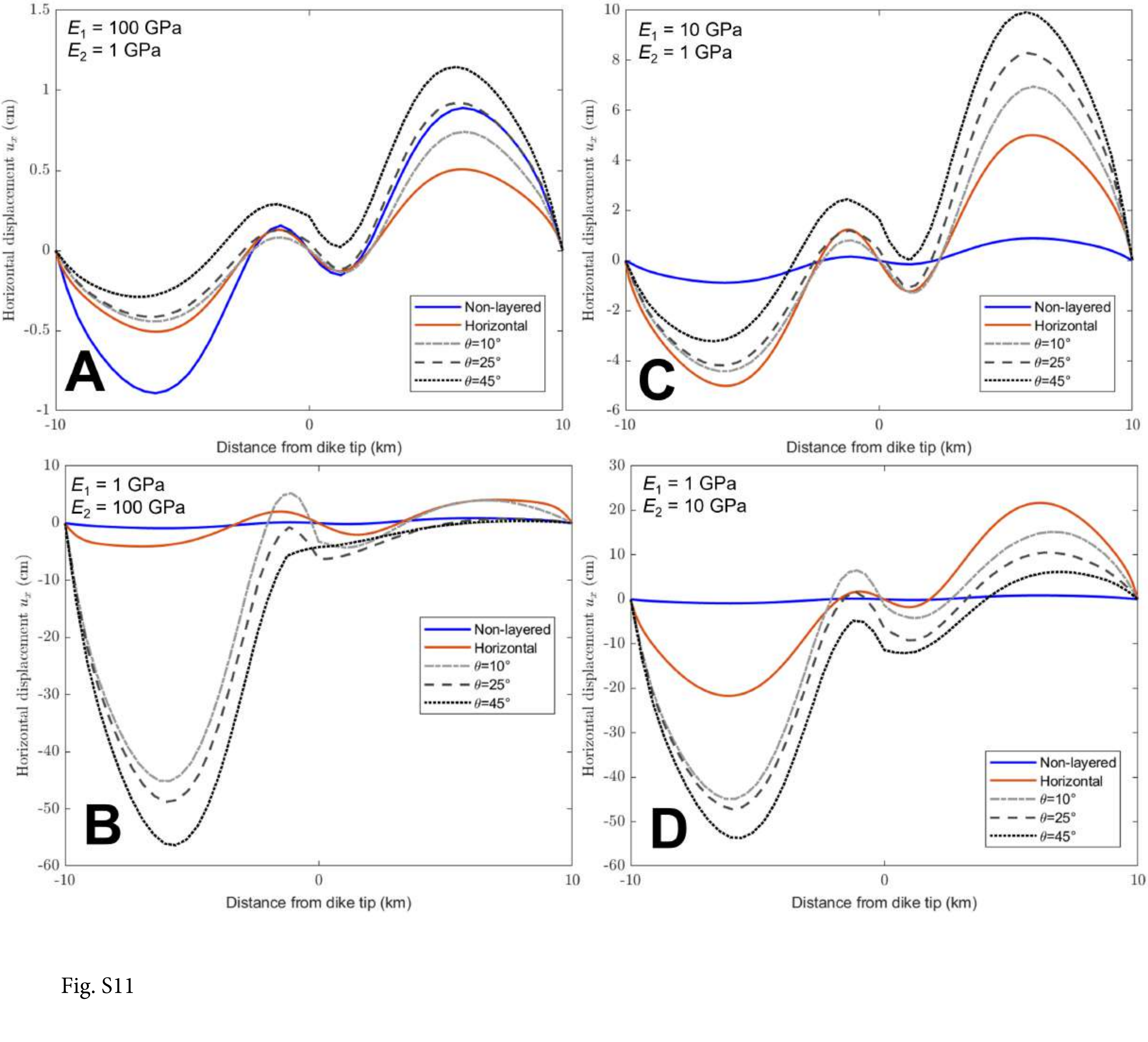
A
E_1 = 100 GPa
E_2 = 1 GPa
B
E_1 = 1 GPa
E_2 = 100 GPa
C
E_1 = 10 GPa
E_2 = 1 GPa
D
E_1 = 1 GPa
E_2 = 10 GPa
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
Horizontal displacement u_x (cm)
Distance from dike tip (km)

Fig. S9



E_1 = 100 GPa
E_2 = 1 GPa
A
E_1 = 10 GPa
E_2 = 1 GPa
C
E_1 = 1 GPa
E_2 = 100 GPa
B
E_1 = 1 GPa
E_2 = 10 GPa
D
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
Horizontal displacement u_x (cm)
Distance from dike tip (km)

Fig. S10



E_1 = 100 GPa
E_2 = 1 GPa
A
E_1 = 10 GPa
E_2 = 1 GPa
C
E_1 = 1 GPa
E_2 = 100 GPa
B
E_1 = 1 GPa
E_2 = 10 GPa
D
Horizontal displacement u_x (cm)
Distance from dike tip (km)
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°

Fig. S11

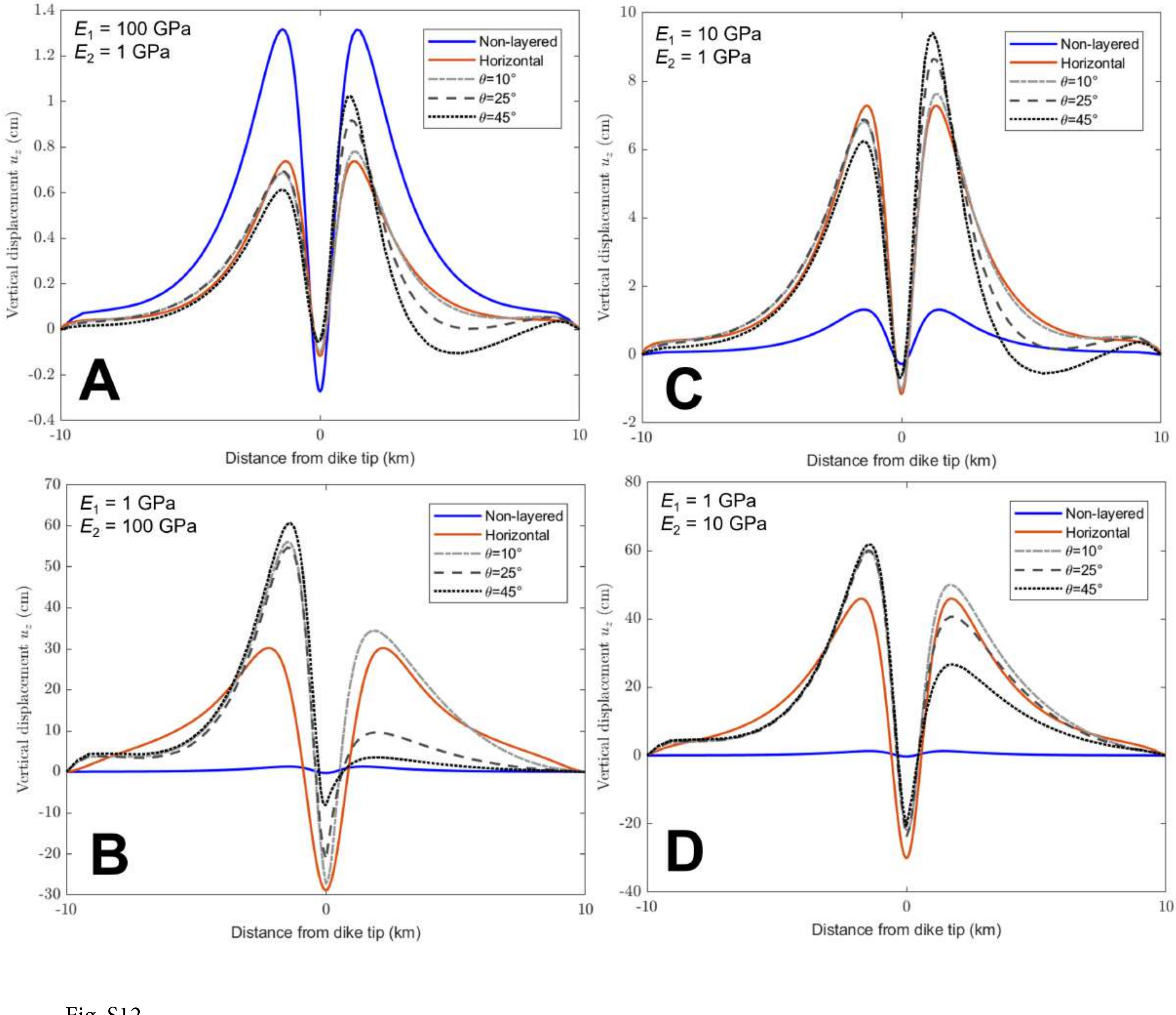
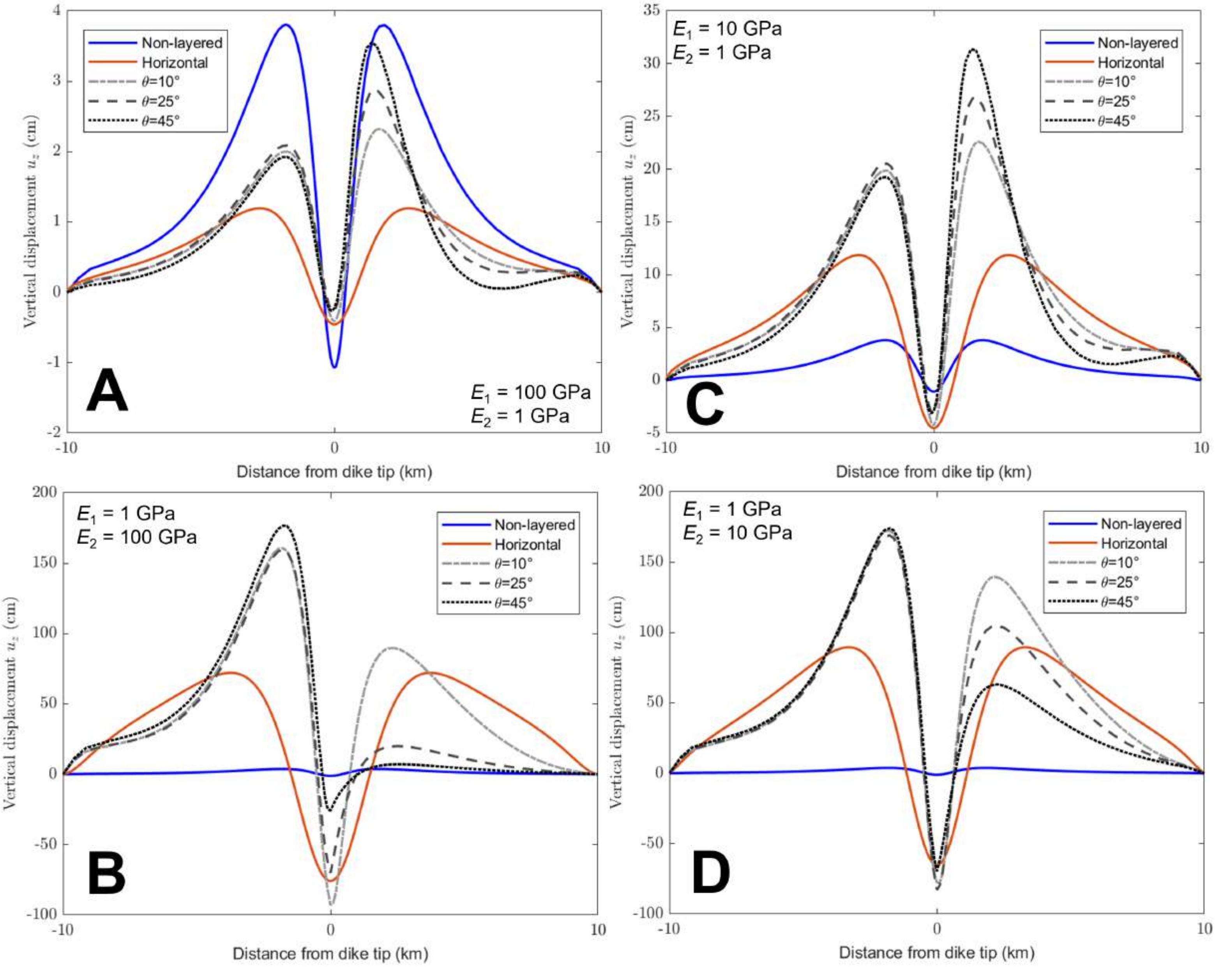
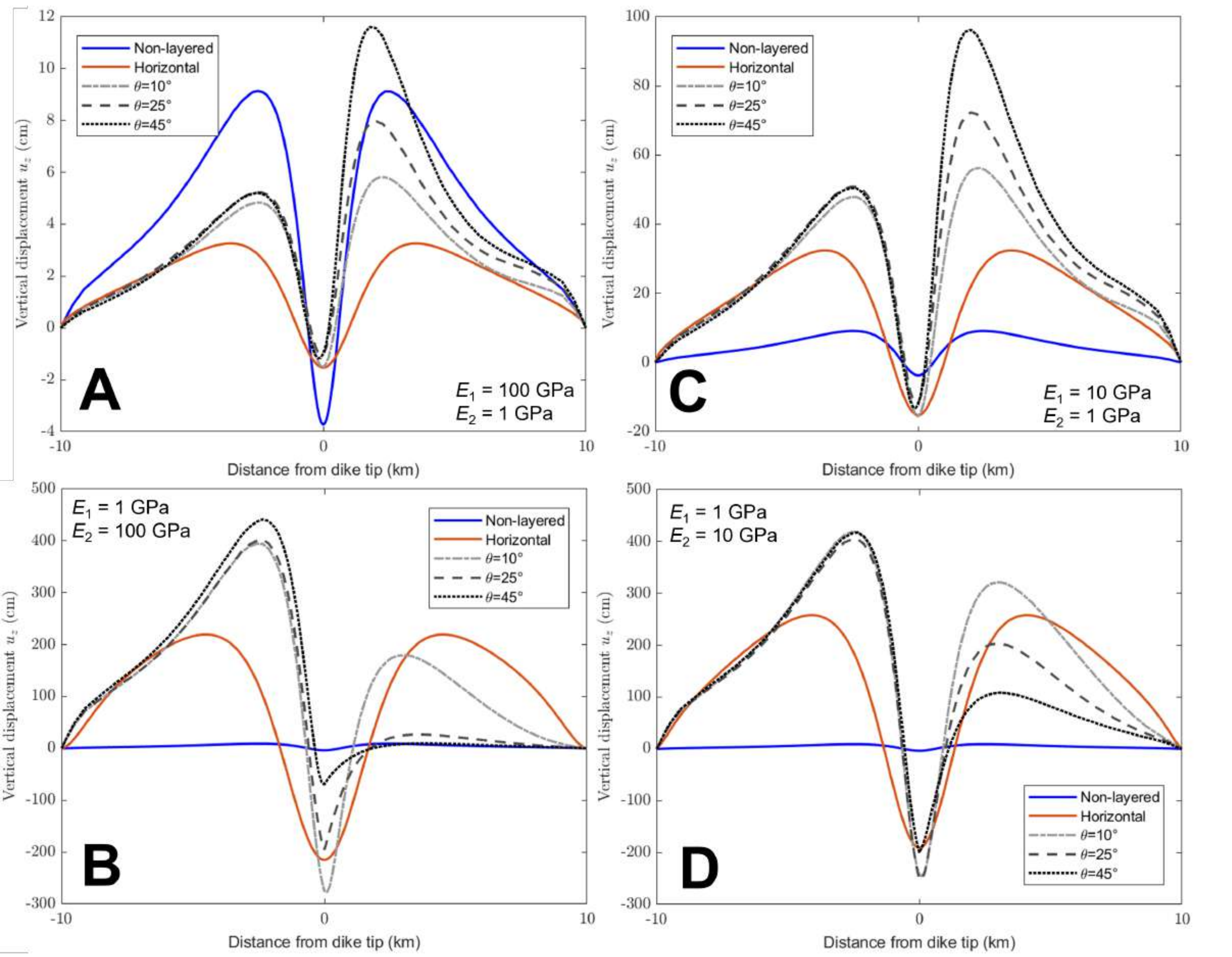

E_1 = 100 GPa
E_2 = 1 GPa
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
A
Vertical displacement u_z (cm)
Distance from dike tip (km)
E_1 = 10 GPa
E_2 = 1 GPa
C
E_1 = 1 GPa
E_2 = 100 GPa
B
E_1 = 1 GPa
E_2 = 10 GPa
D

Fig. S12



A
E_1 = 100 GPa
E_2 = 1 GPa
C
E_1 = 10 GPa
E_2 = 1 GPa
B
E_1 = 1 GPa
E_2 = 100 GPa
D
E_1 = 1 GPa
E_2 = 10 GPa
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
Vertical displacement u_z (cm)
Distance from dike tip (km)

Fig. S13



A
E_1 = 100 GPa
E_2 = 1 GPa
C
E_1 = 10 GPa
E_2 = 1 GPa
B
E_1 = 1 GPa
E_2 = 100 GPa
D
E_1 = 1 GPa
E_2 = 10 GPa
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
Vertical displacement u_z (cm)
Distance from dike tip (km)

Fig. S14

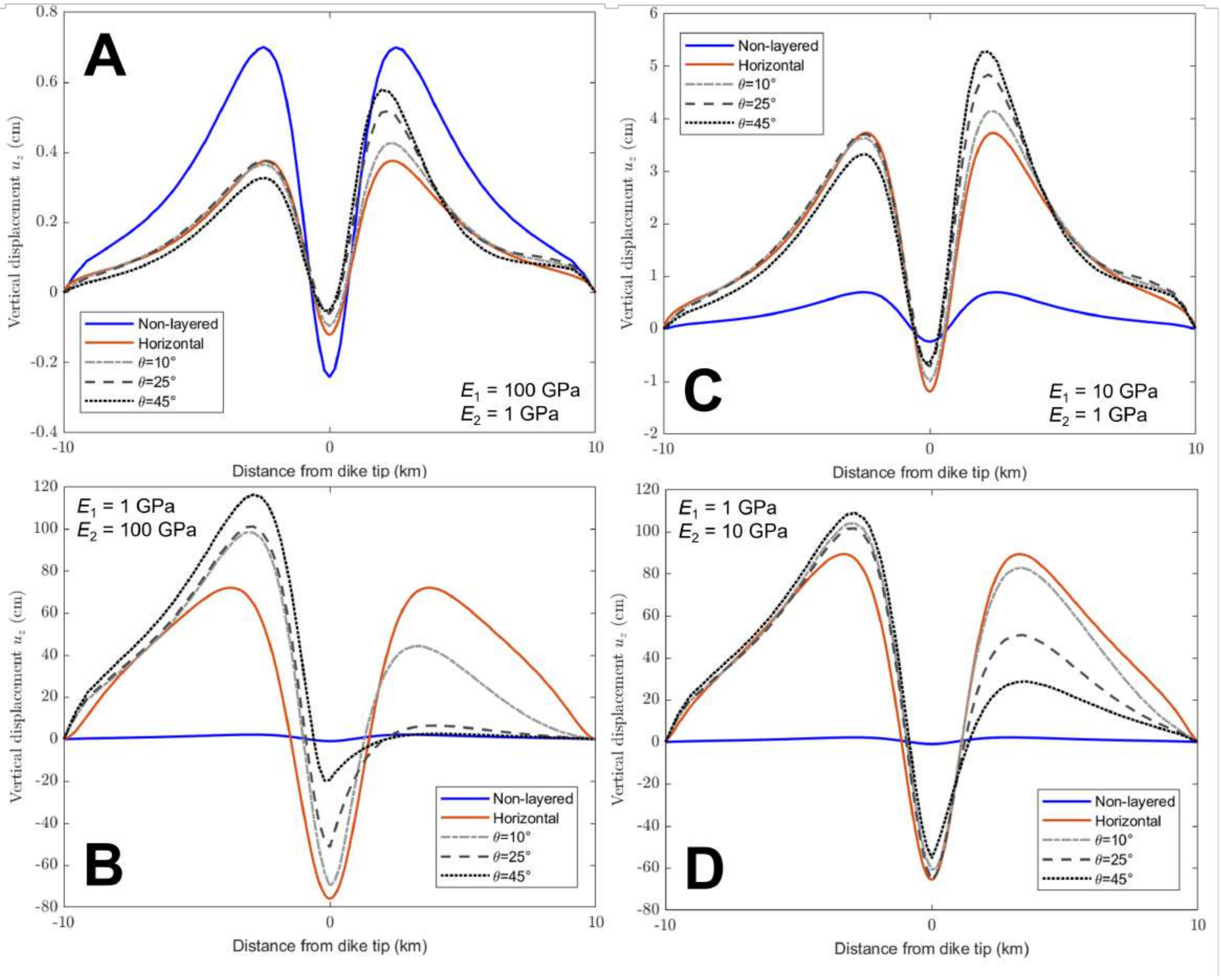

A
B
C
D
Vertical displacement u_z (cm)
Distance from dike tip (km)
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
E_1 = 100 GPa
E_2 = 1 GPa
E_1 = 10 GPa
E_2 = 1 GPa
E_1 = 1 GPa
E_2 = 100 GPa
E_1 = 1 GPa
E_2 = 10 GPa

Fig. S15

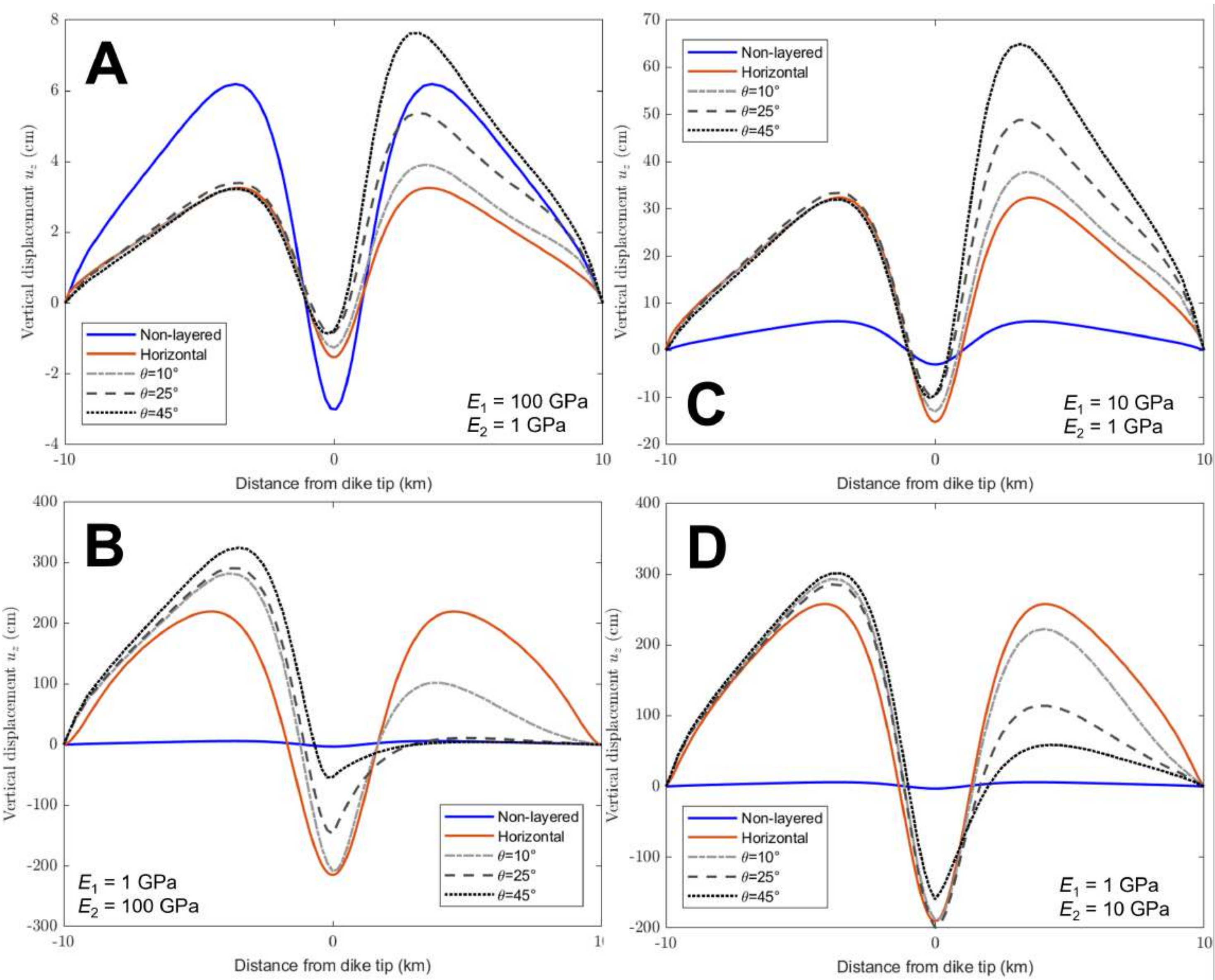

A
B
C
D
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
E1 = 100 GPa
E2 = 1 GPa
E1 = 1 GPa
E2 = 100 GPa
E1 = 10 GPa
E2 = 1 GPa
E1 = 1 GPa
E2 = 10 GPa
Vertical displacement uz (cm)
Distance from dike tip (km)

Fig. S16

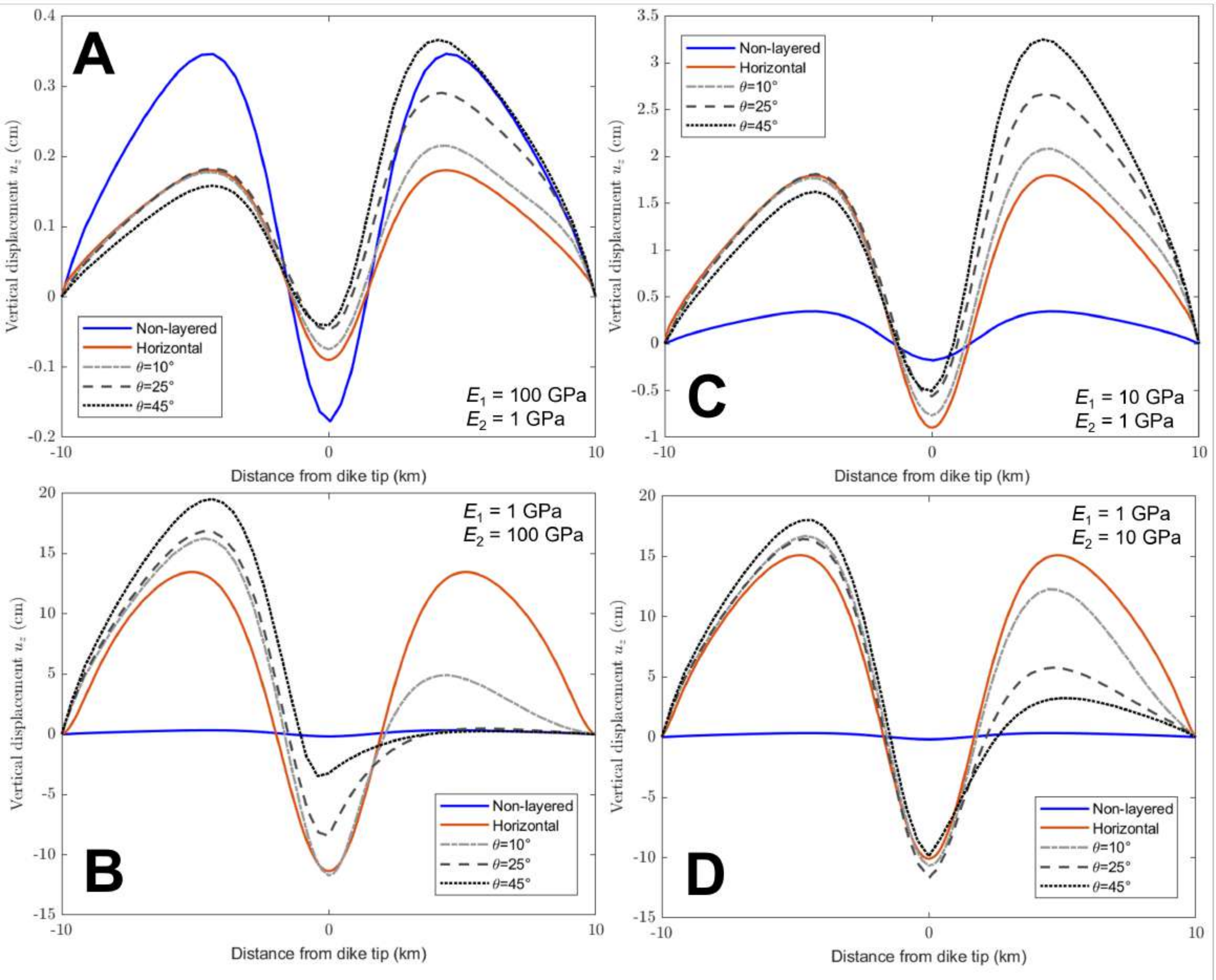

A
B
C
D
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
E1 = 100 GPa
E2 = 1 GPa
E1 = 10 GPa
E2 = 1 GPa
E1 = 1 GPa
E2 = 100 GPa
E1 = 1 GPa
E2 = 10 GPa
Vertical displacement uz (cm)
Distance from dike tip (km)

Fig. S17

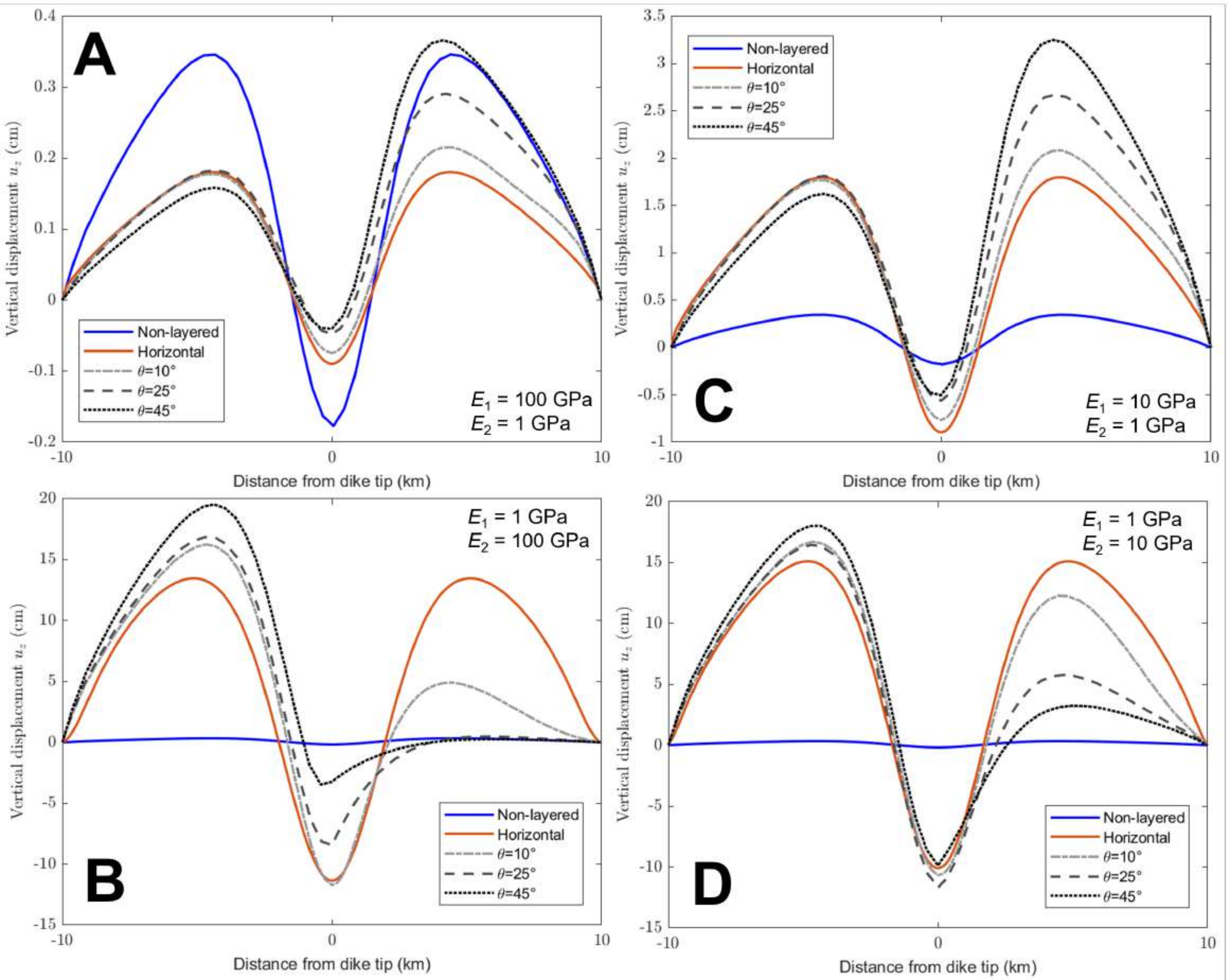

A
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
E_1 = 100 GPa
E_2 = 1 GPa
Vertical displacement u_z (cm)
Distance from dike tip (km)
C
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
E_1 = 10 GPa
E_2 = 1 GPa
Vertical displacement u_z (cm)
Distance from dike tip (km)
B
E_1 = 1 GPa
E_2 = 100 GPa
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
Vertical displacement u_z (cm)
Distance from dike tip (km)
D
E_1 = 1 GPa
E_2 = 10 GPa
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
Vertical displacement u_z (cm)
Distance from dike tip (km)

Fig. S18

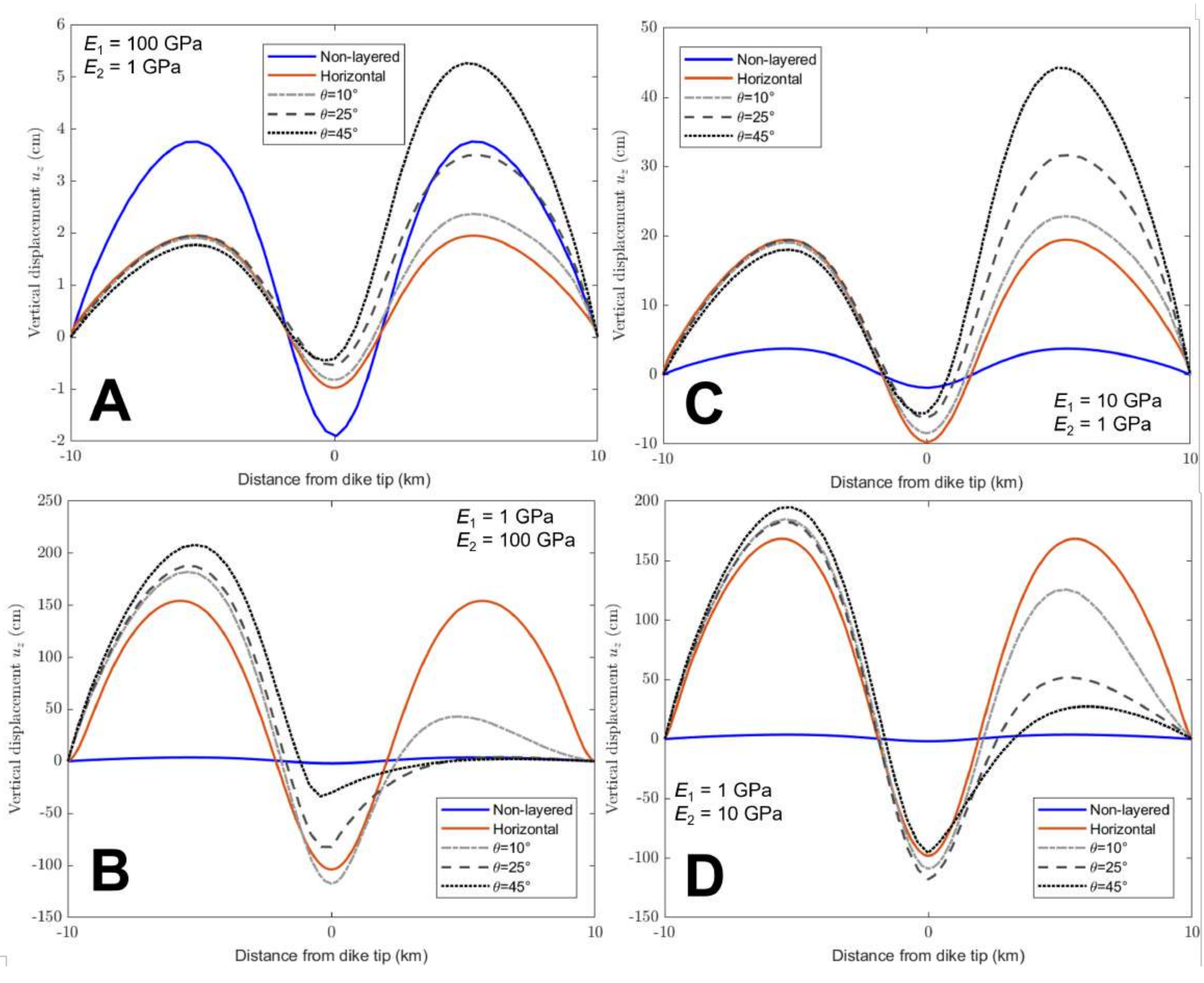

E1 = 100 GPa
E2 = 1 GPa
Non-layered
Horizontal
θ=10°
θ=25°
θ=45°
A
Vertical displacement uz (cm)
Distance from dike tip (km)
E1 = 10 GPa
E2 = 1 GPa
C
E1 = 1 GPa
E2 = 100 GPa
B
E1 = 1 GPa
E2 = 10 GPa
D

Fig. S19