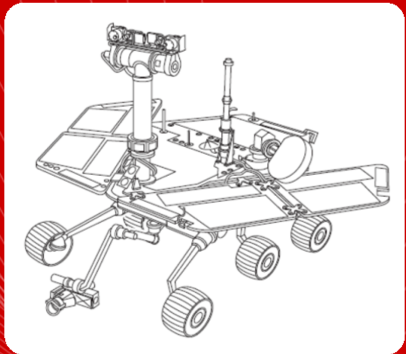

2011 Users Conference

# Dynamic Modeling and Soil Mechanics for Path Planning of the Mars Exploration Rovers

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Pasadena, CA



AM-User12-010

MSC Software

# ABSTRACT

To help minimize risk of high sinkage and slippage during drives and to better understand soil properties and rover terramechanics from drive data, a multidisciplinary team was formed under the **Mars Exploration Rover** project to develop and utilize dynamic computer-based models for rover drives over realistic terrains. The resulting system, named **ARTEMIS** (Adams-based Rover Terramechanics and Mobility Interaction System), consists of the dynamic model, a library of terramechanics subroutines, and the high-resolution digital elevation maps of the Mars surface. A 200-element model of the rovers was developed and validated for drop tests before launch, using **Adams** dynamic modeling software. The external library was built in Fortran and called by **Adams** to model the wheel-soil interactions include the rut-formation effect of deformable soils, lateral and longitudinal forces, bull-dozing effects, and applied wheel torque. The paper presents the details and implementation of the system. To validate the developed system, one study case is presented from a realistic drive on Mars of the Opportunity rover. The simulation results match well from the measurement of on-board telemetry data. In its final form, **ARTEMIS** will be used in a predictive manner to assess terrain navigability and will become part of the overall effort in path planning and navigation for both Martian and lunar rovers.

# Mars Rover Mobility Campaigns


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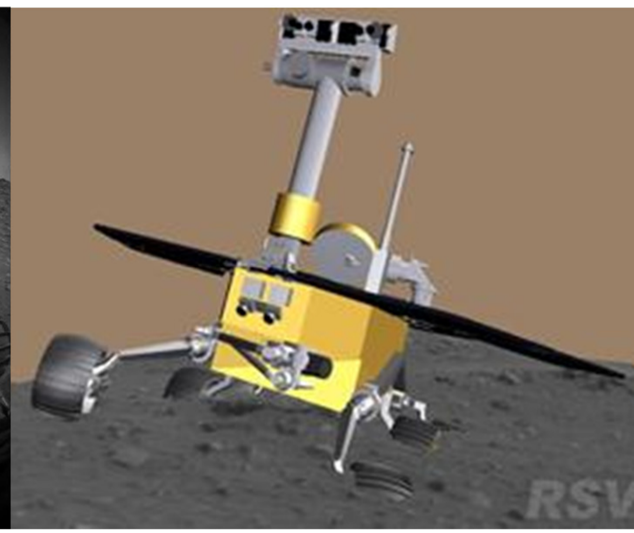
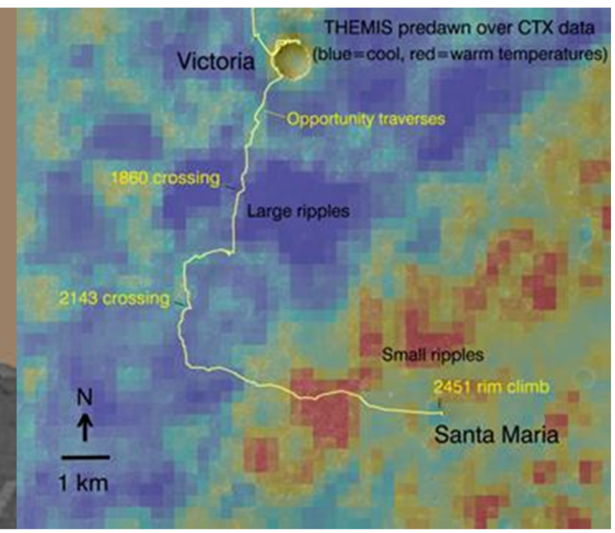


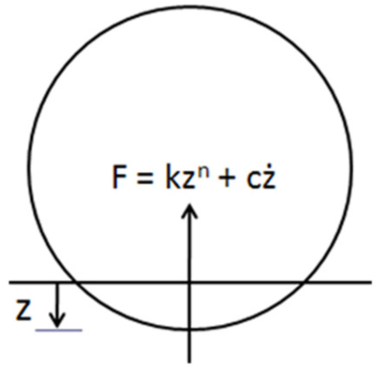
# MER Mission Overview

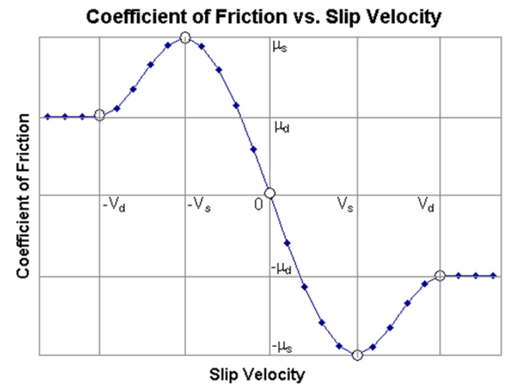
- NASA Mars surface exploration program based on mobile robots (rovers)
- Pathfinder mission (Sojourner)
  - July, 1997—Sept 1997
- Mars Exploration rovers (Spirit and Opportunity)
  - 2004—2010 (Spirit) ; Opportunity still functioning
- Mars Science Laboratory (Curiosity)
  - Launch in November 2011

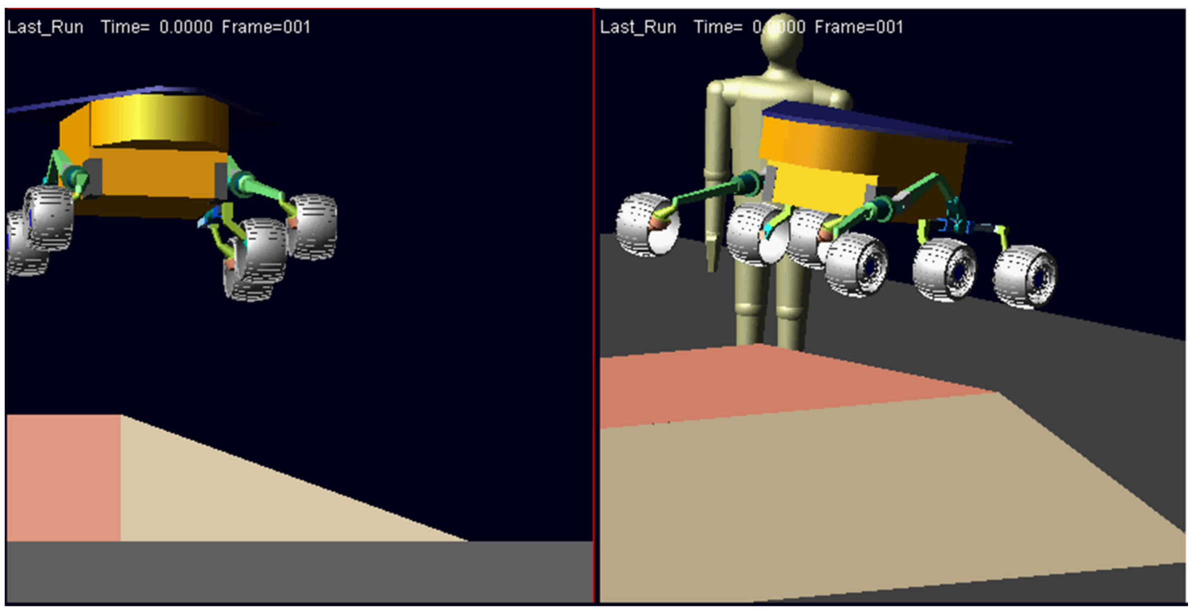
# Rover Comparison

# ADAMS Rover Model

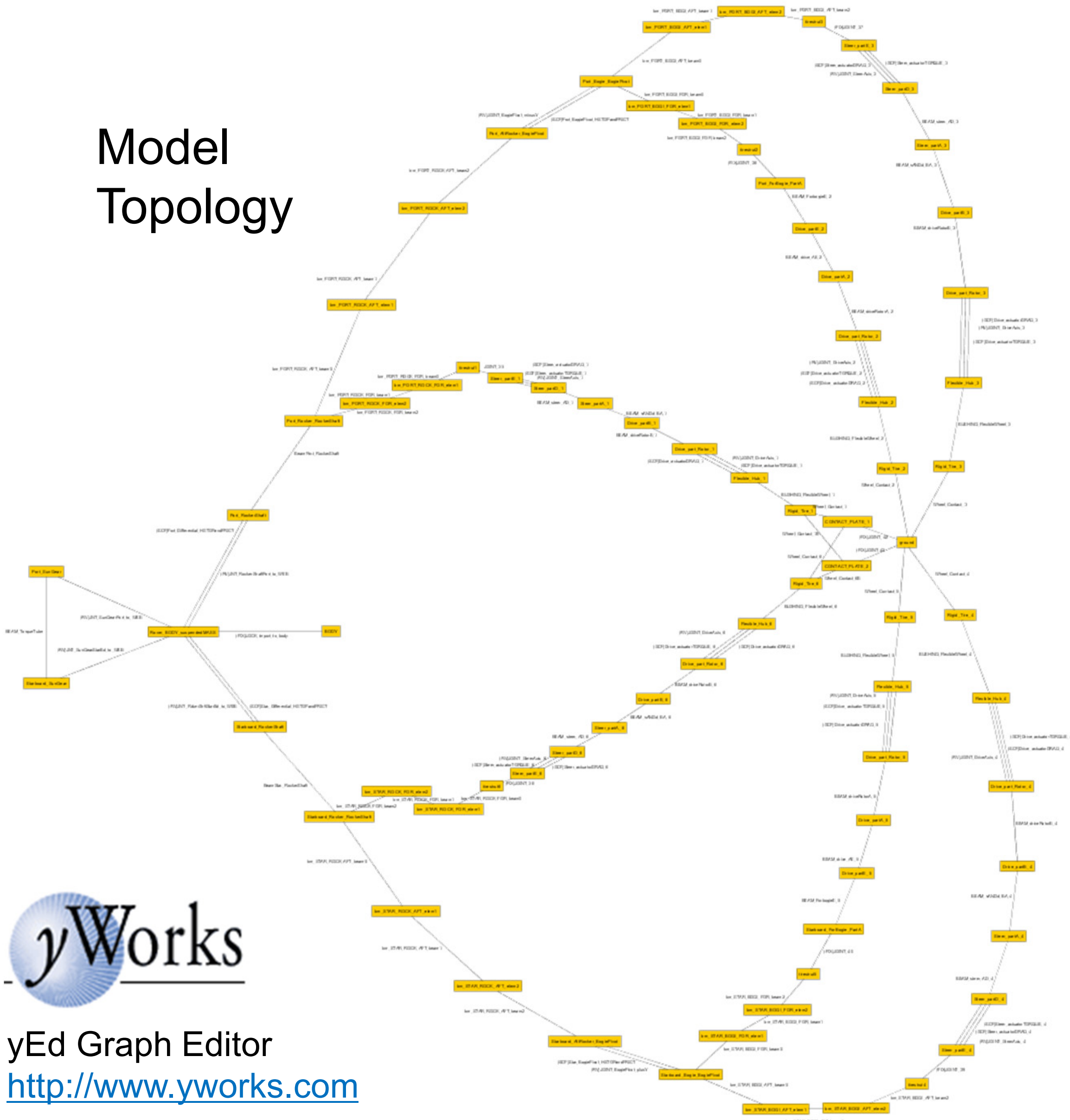
- Developed and previously reported by Randy Lindemann, JPL
- Simplified Contact Model
- Drop Test



Model
Topology



# ADAMS Model Detail

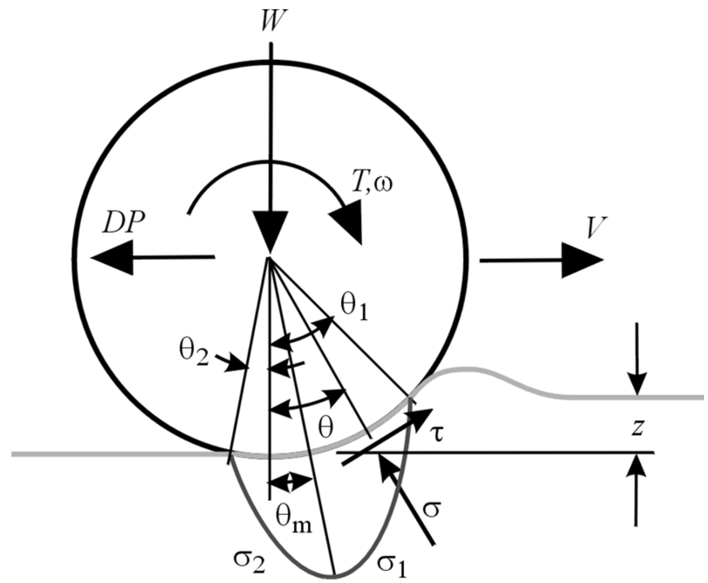
VERIFY MODEL:

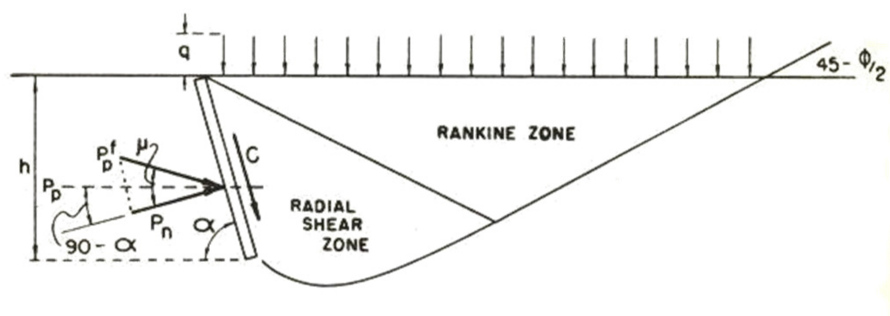
- 316 Gruebler Count (approximate degrees of freedom)
- 76 Moving Parts (not including ground)
- 12 Revolute Joints
- 13 Fixed Joints
- 2 Couplers

yEd Graph Editor
http://www.yworks.com

# Surface Interaction Modeling

- Parametric methods for surface interaction modeling
  - Strengths
    - Physics-based models employ measurable physical parameters
    - Computationally efficient
    - Applicability to many soil types
  - Weaknesses
    - Ignore some important effects (rate, soil state, material transport)
    - Scaling of classical models is questionable
  - **Bekker-Wong** Classical Terramechanics Formulation



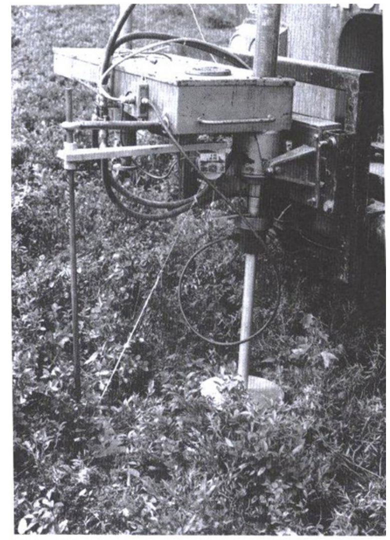
# Pressure-Sinkage

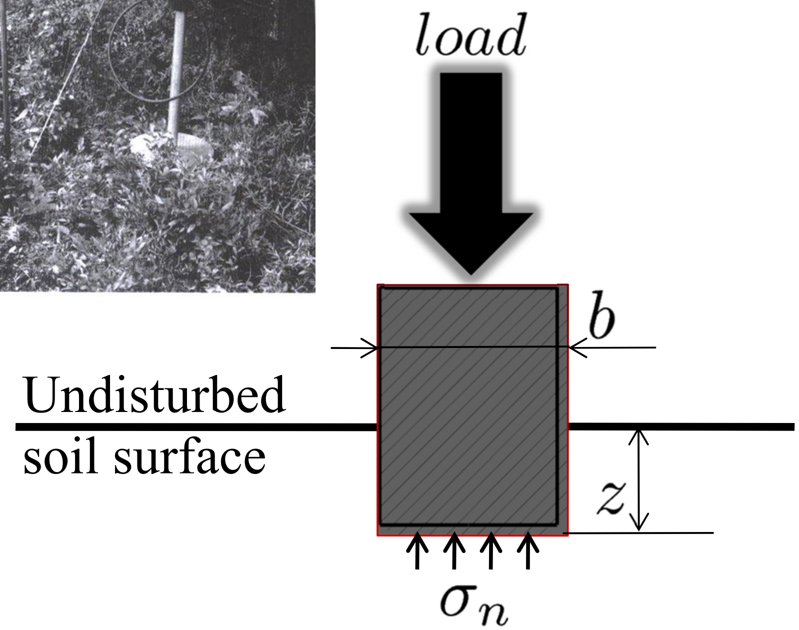
- Pressure-sinkage relationship for geomaterials

$$\sigma = kz^n$$

  - σ is normal pressure
  - *k* is empirical constant
  - *z* is sinkage from free surface

- Bekker proposed semi-empirical formulation






Cohesion-dependent soil coefficient

Friction-dependent soil coefficient

$$\sigma_n = \left( \frac{k_c}{b} + k_\phi \right) z^n$$

Sinkage exponent

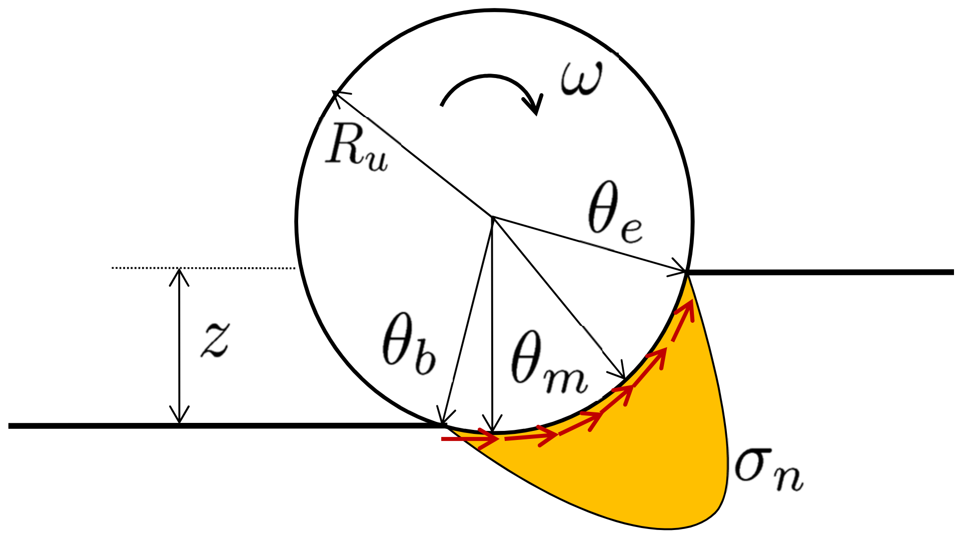
M. G. Bekker. *Theory of Land Locomotion*. Ann Arbor, University of Michigan Press, 1950.

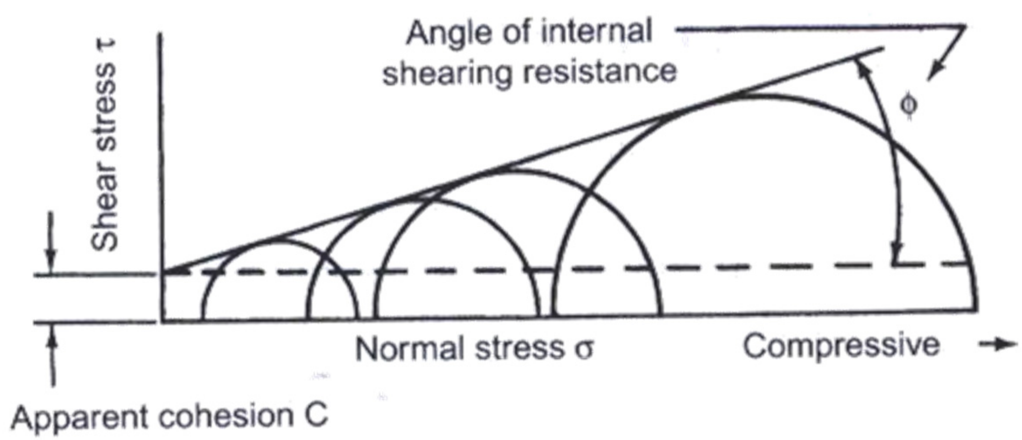
# Shearing Properties of Soil

- Shear stress at wheel-soil interface produces traction
- Shear stress is a function of shear displacement
  - Relative motion required to generate traction
    - Non-zero slip ratio
- Soil failure estimated through Mohr-Coulomb failure criterion

$$\tau = c + \sigma \tan \phi$$

  - $\tau$ is failure stress
  - $c$ is soil cohesion
  - $\phi$ is soil internal friction angle



# Shearing Properties of Soil

- Can compute shear stress at wheel-terrain interface
  - Janosi-Hanamoto formulation

Soil shear displacement

Limit tangential stress

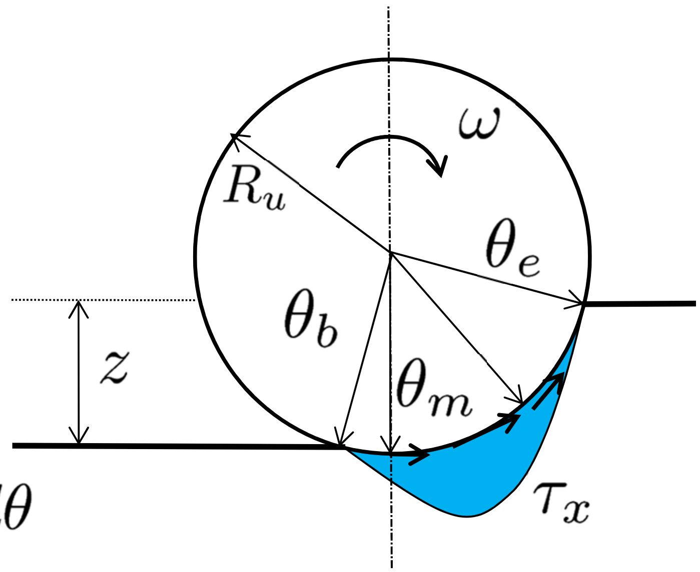
$$\tau_x(\theta) = \tau_{max}\left(1 - e^{\frac{-j_x}{k_x}}\right)$$

Soil shear deformation modulus

$$\tau_{max} = c + \sigma_n(\theta)\tan\phi$$

- Soil shear displacement

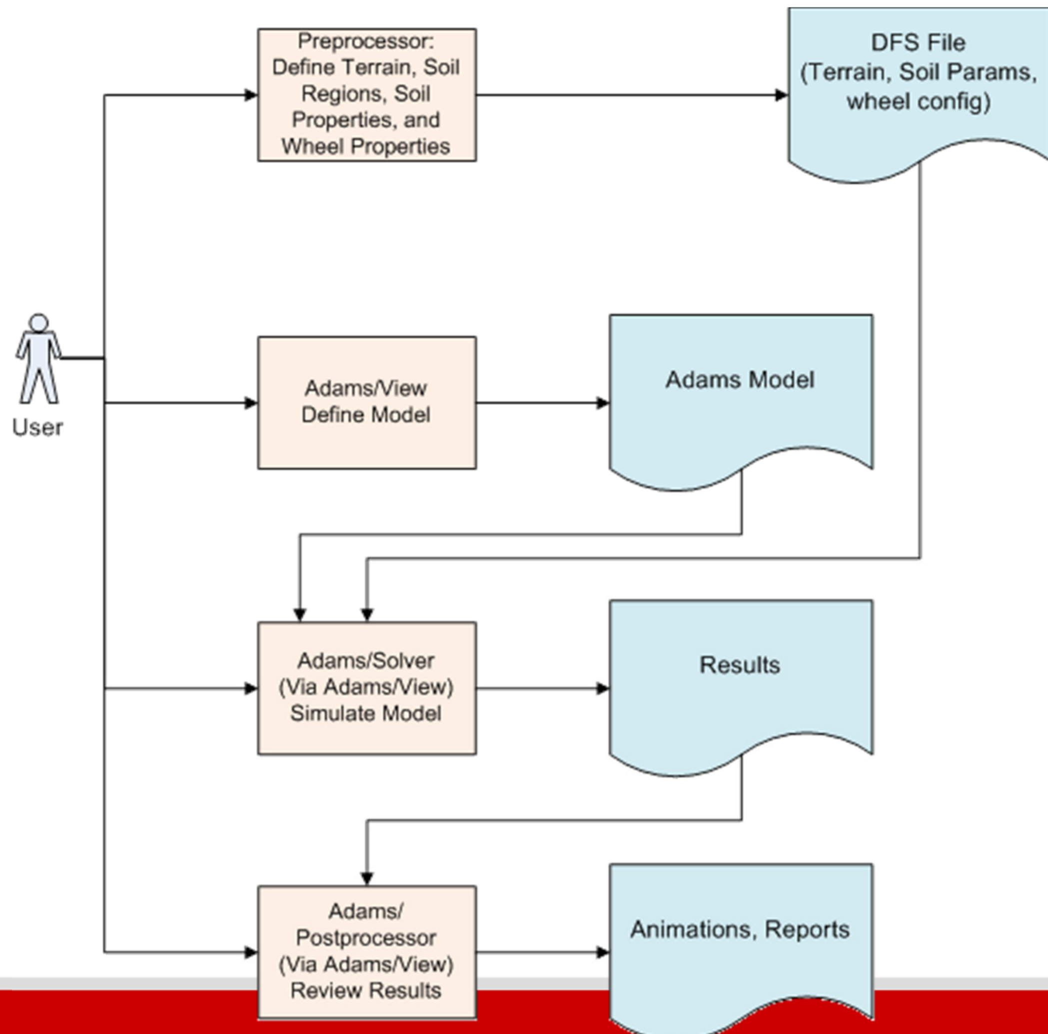
$$j_x(\theta) = \int_{\theta_b}^{\theta_e} R_u[1 - (1 - s_d)\cos(\theta)]\, d\theta$$




Z. Janosi and B. Hanamoto. Analytical determination of drawbar pull as a function of slip for tracked vehicles in deformable soils, Proc. ISTVS

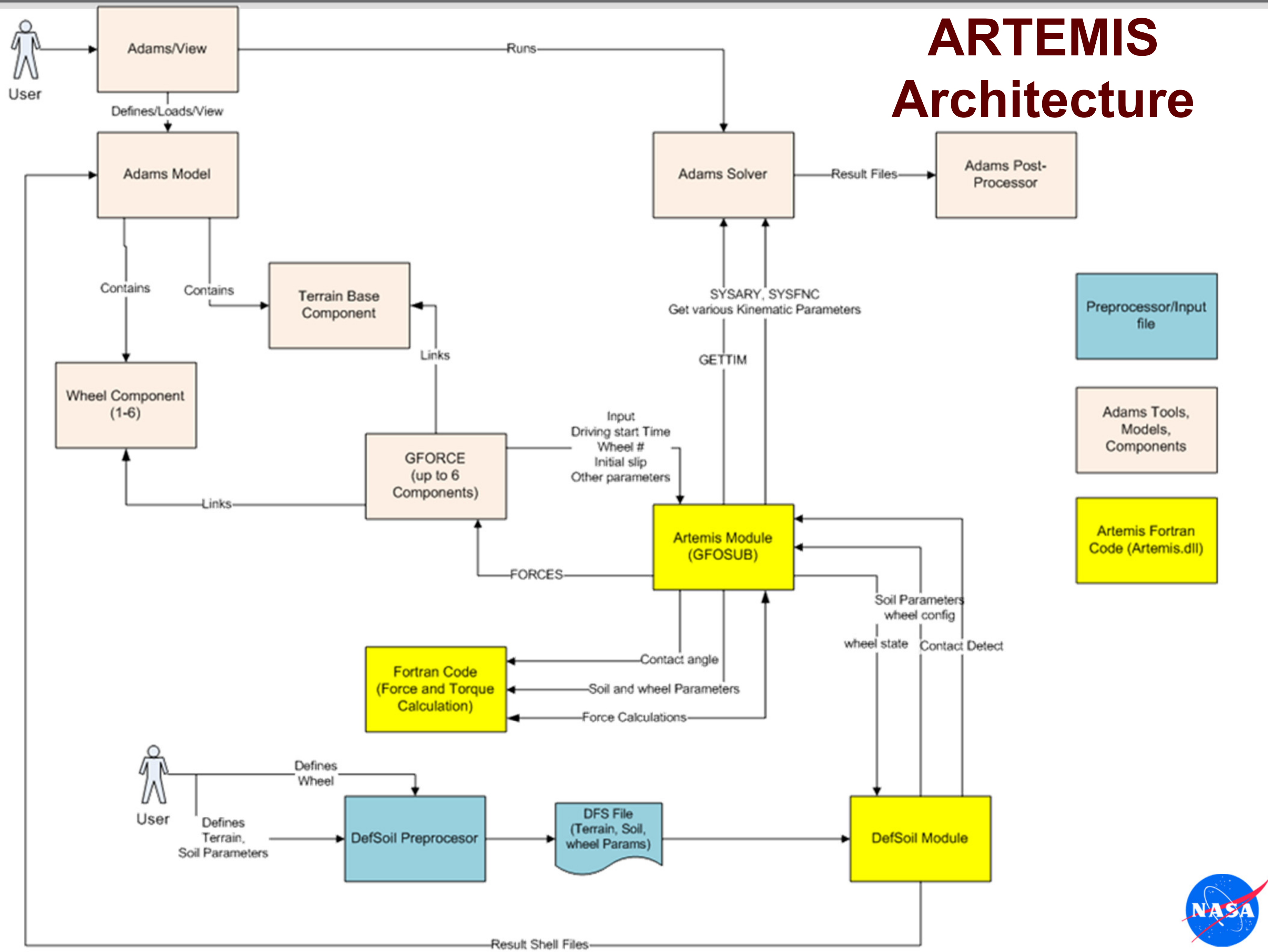
# ARTEMIS

**A**dams-based **R**over **Te**rramechanics and **M**obility **I**nteraction **S**imulator

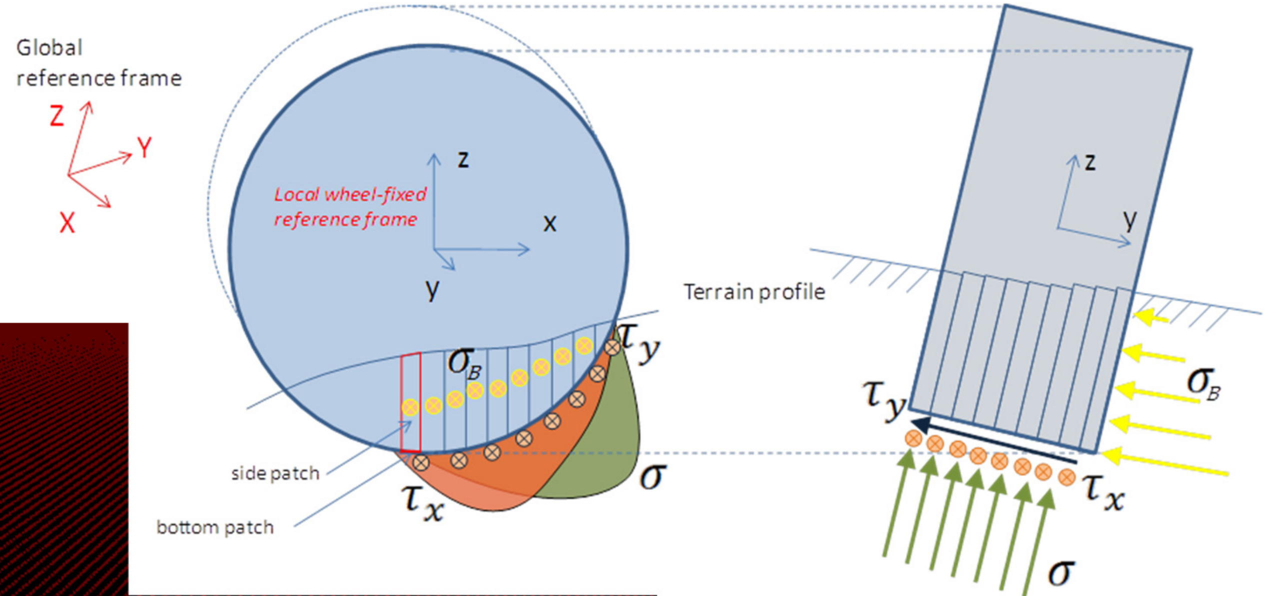



MIT
Washington University in St.Louis
JPL

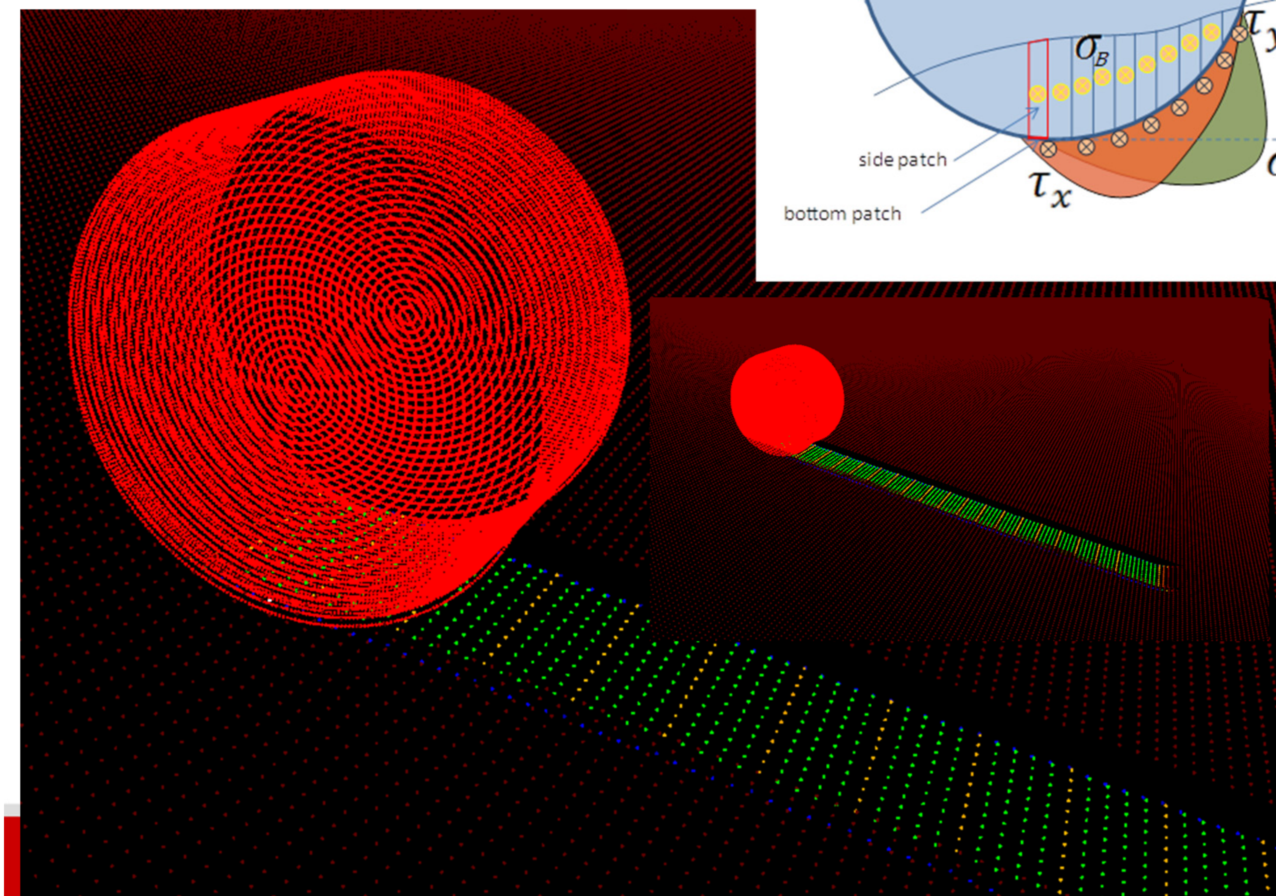
# ARTEMIS Architecture



# Contact Engine and Patch Model



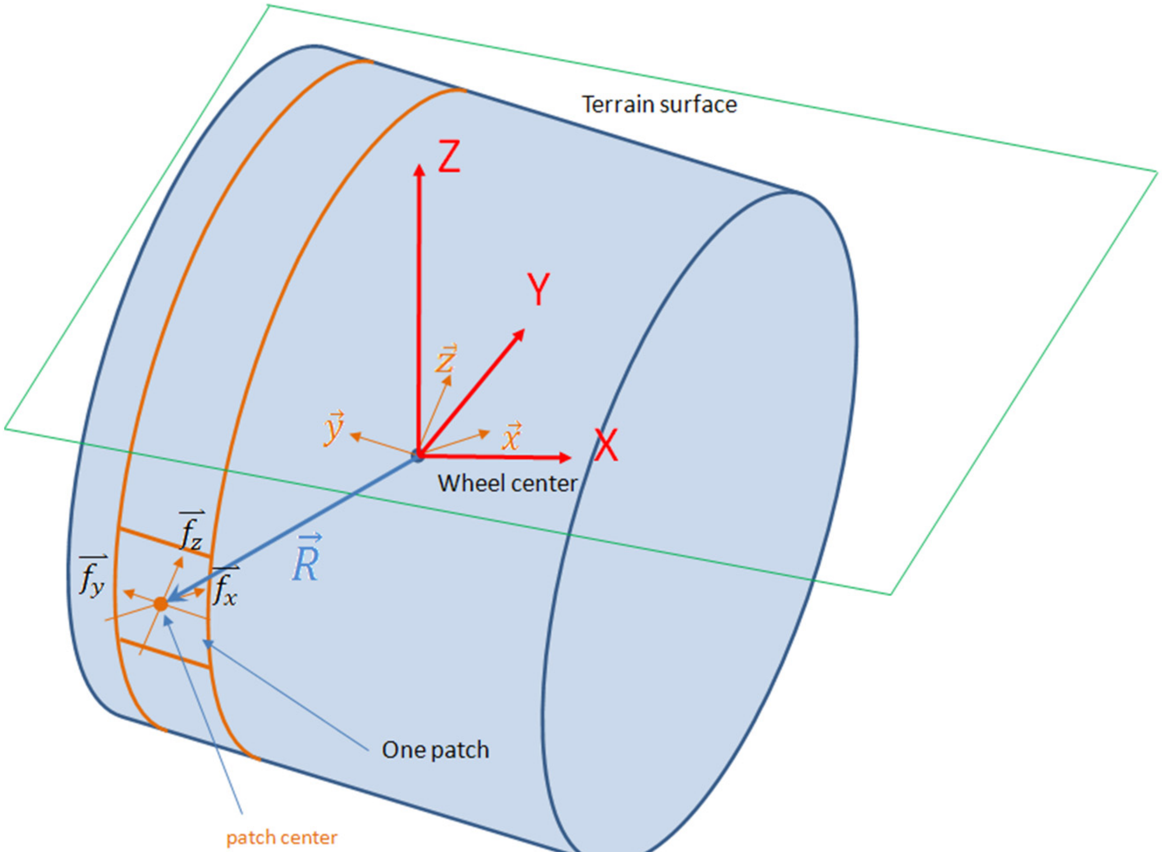

Terrain/Wheel
Contact Engine in
Fortran/C-sharp



Coordinate Frame and
Representation of Wheel and
Soil for Terramechanics
Analysis

Discretized Slices

# Global/Local Coordinate Frames and Summations




$$T = br\int_{\theta_r}^{\theta_f} \tau \cos\theta \, d\theta$$

$$R_c = br\int_{\theta_r}^{\theta_f} \sigma \sin\theta \, d\theta$$

$$DP = T - R_c + F_g$$

$$L = F_u + F_b \sin\beta$$

$$N = br\int_{\theta_r}^{\theta_f} (\sigma\cos\theta + \tau\sin\theta)d\theta + \sum F_g \sin\theta$$

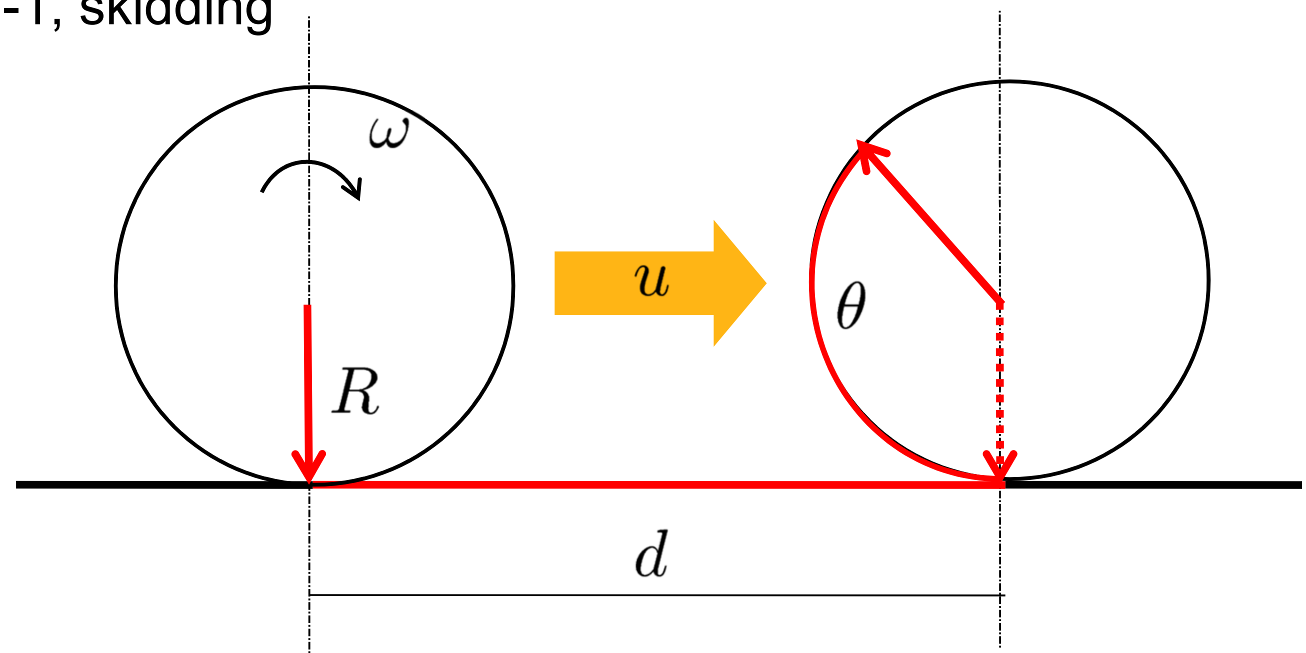
# Slip Ratio

- Slip ratio is measure of relative motion between wheel and terrain surface
  - For driven wheel, distance traveled is less than that in free rolling
  - When slip ratio = 1, spinning in place
  - When slip ratio = 0, pure rolling
  - When slip ratio = -1, skidding

$$u \leq \omega R$$

$$d \leq \theta R$$

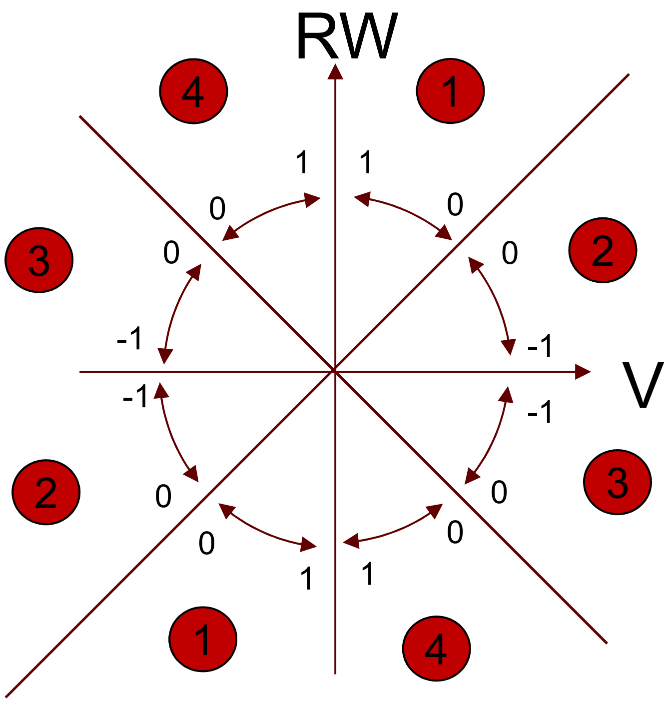
$$s_d = 1 - \frac{u}{\omega R}$$



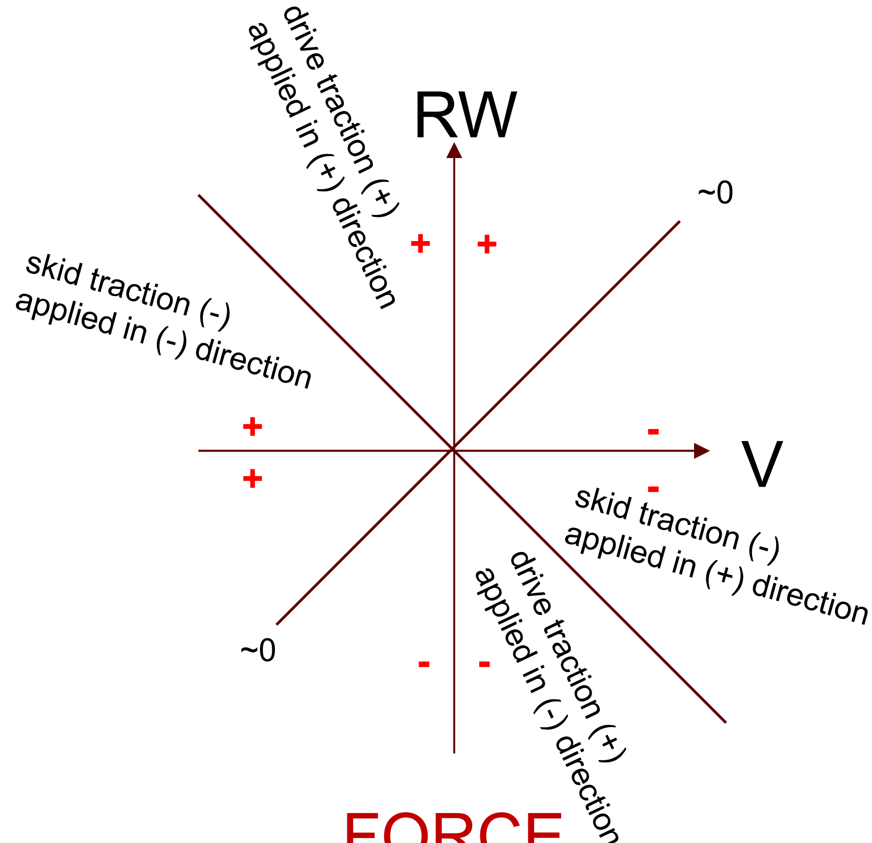
# Slip Modeling

$$i = \begin{cases} 1 - \dfrac{v}{r\omega} & (if\ \ v < r\omega\ driving) \quad ① \\ \dfrac{r\omega}{v} - 1 & (if\ \ v > r\omega\ braking) \quad ② \end{cases}$$

$$i = \begin{cases} 1 + \dfrac{v}{r\omega} & (if\ \ \dfrac{r\omega}{v} < -1) \quad ④ \\ -\dfrac{r\omega}{v} - 1 & (if\ \ -1 < \dfrac{r\omega}{v} < 0) \quad ③ \end{cases}$$




SLIP

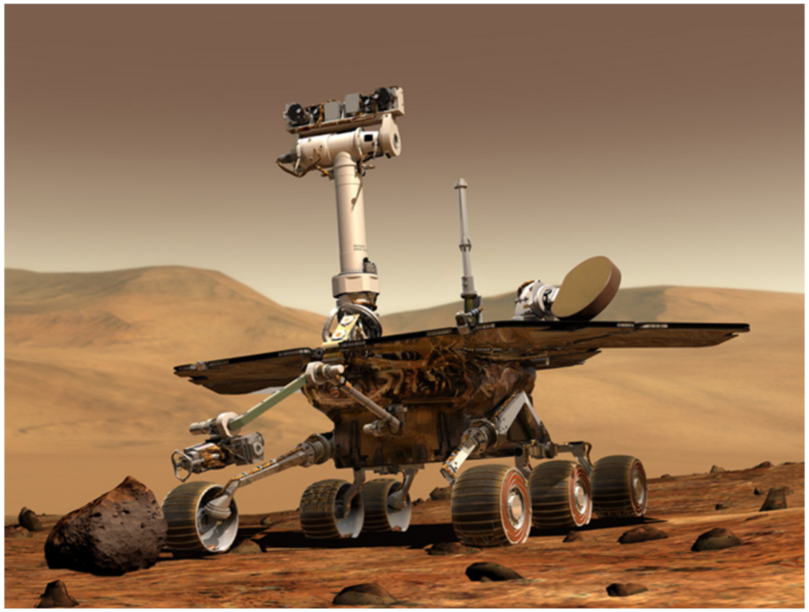


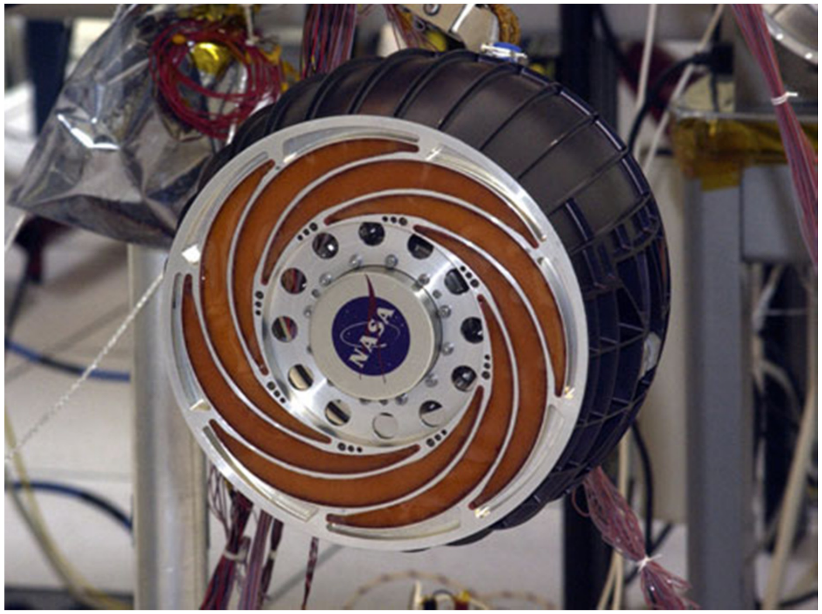

FORCE

# Case Studies: Rover Design & Performance Prediction

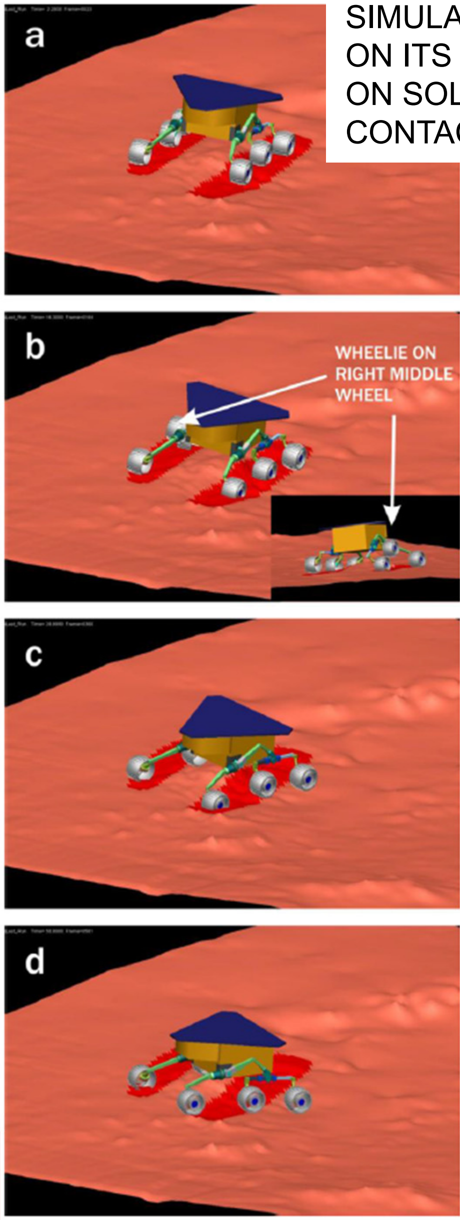
- MER Rover
  - Lightweight, 6 wheels, rocker-bogie suspension system
- Wheel diameter 26 cm
- Static vertical load on each wheel ~ 100N
- Landing site area composed of bedrock outcrops, loose, sandy material

| Terrain Parameters | | Dry Sand |
|---|---|---|
| $n$ | (sinkage exponent) | 0.705 |
| $k_c$ | (cohesion parameter) | 6.94 [kN/m$^{n+1}$] |
| $k_\phi$ | (angle of internal friction parameter) | 505.8 [kN/m$^{n+2}$] |
| $c$ | (cohesion) | 960 [N/m$^2$] |
| $\phi$ | (angle of internal friction) | 27.3 [deg] |
| $k_x$ | (shear modulus) | 0.0114 [m] |

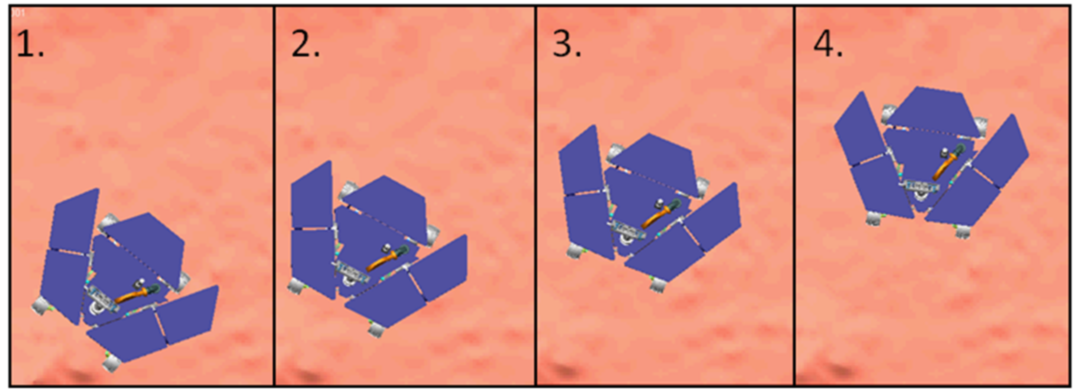




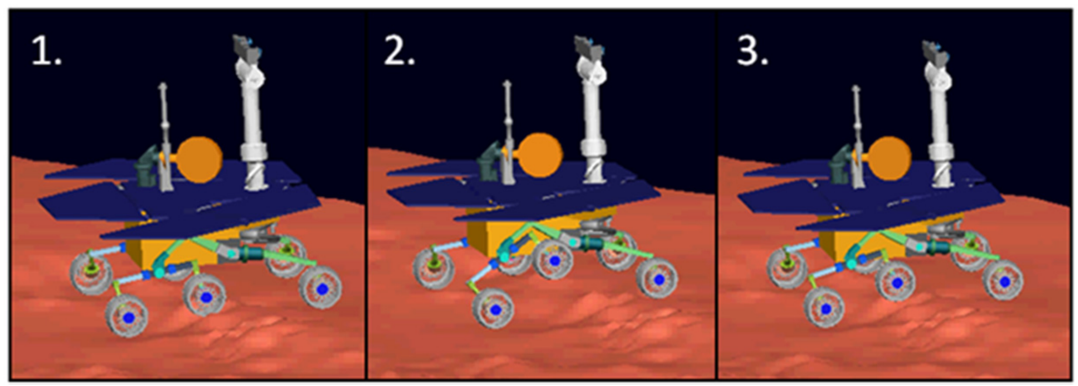
# Spirit Rover at Troy




SIMULATION OF SPIRIT ON ITS DRIVE INTO TROY ON SOL 1871 (SIMPLIFIED CONTACT MODEL)



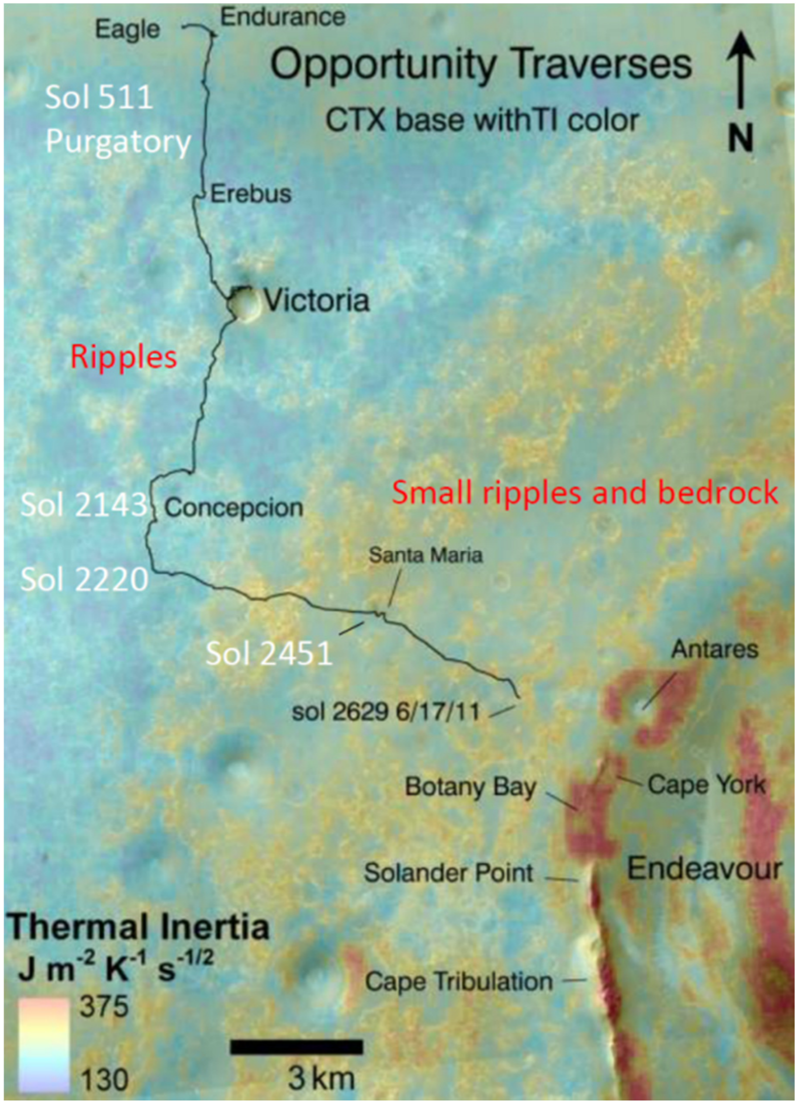

YAW EXHIBITED DURING A 4-WHEEL BACKWARD DRIVE SIMULATION.
OPERABLE WHEELS: STATIC COF= 0.5, DYNAMIC COF=0.4;
WHEELS 4 AND 6: STATIC COF=0.7, DYNAMIC COF=0.6



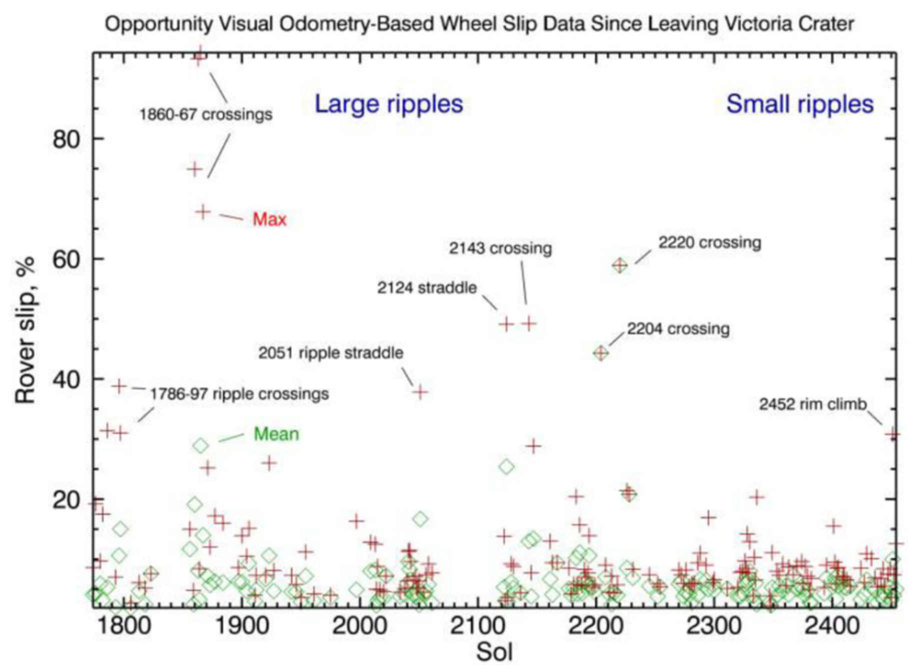

STICK-SLIP MOTION EXHIBITED DURING A 4-WHEEL BACKWARD DRIVE SIMULATION.
OPERABLE WHEELS: STATIC COF= 0.5, DYNAMIC COF=0.4;
WHEELS 4 AND 6: STATIC COF=0.7, DYNAMIC COF=0.6

(SOL = Mars DAY)

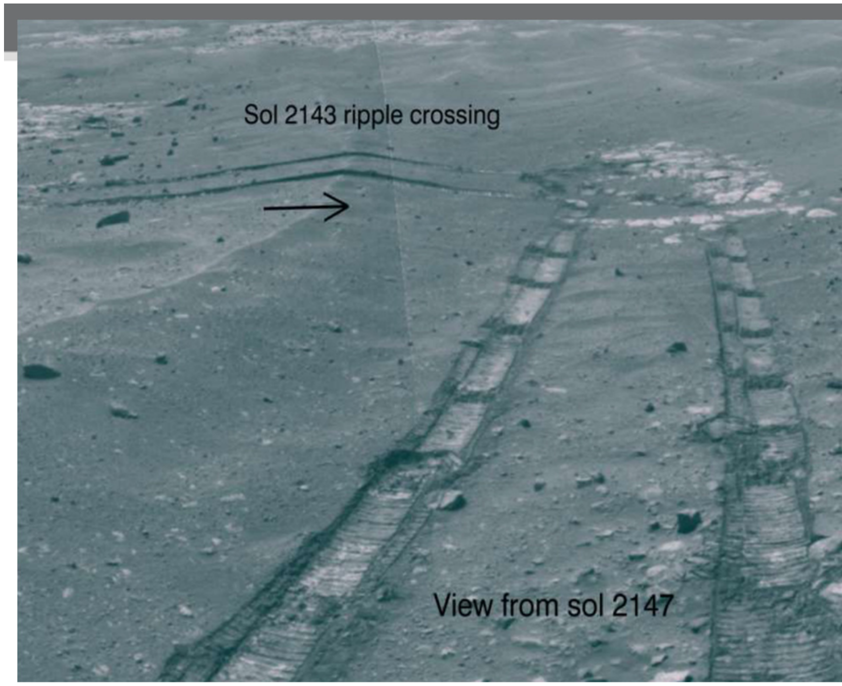
# Ripples

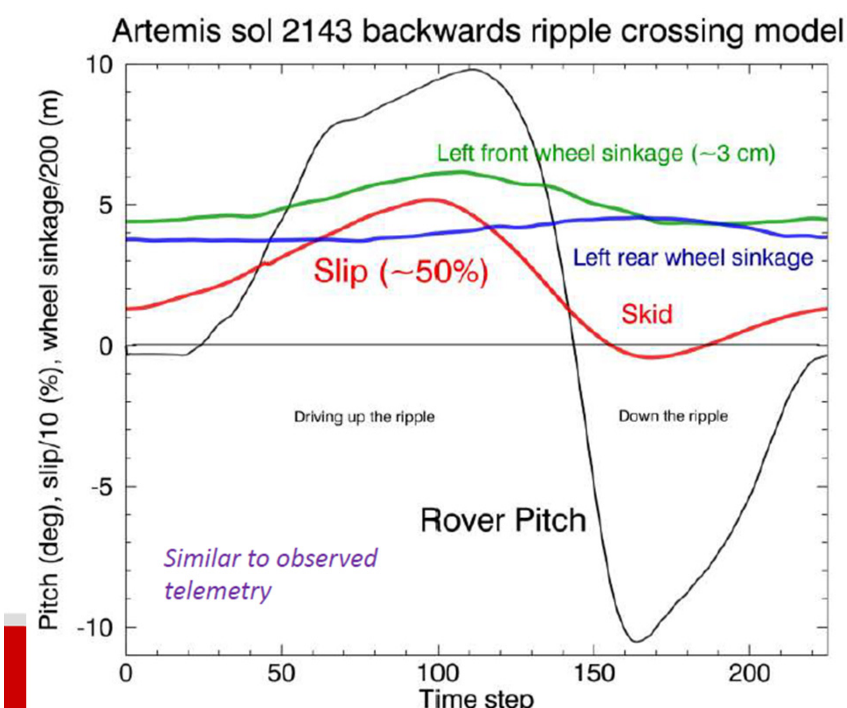


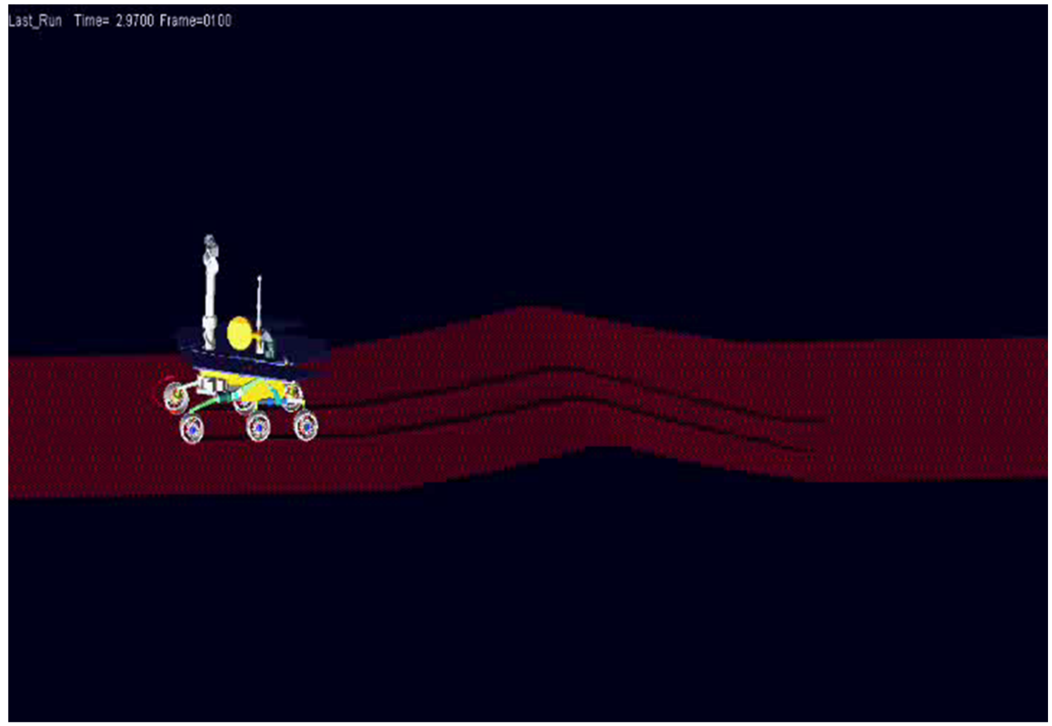

(SOL = Mars DAY)

# Opportunity Rover Ripple Experiments



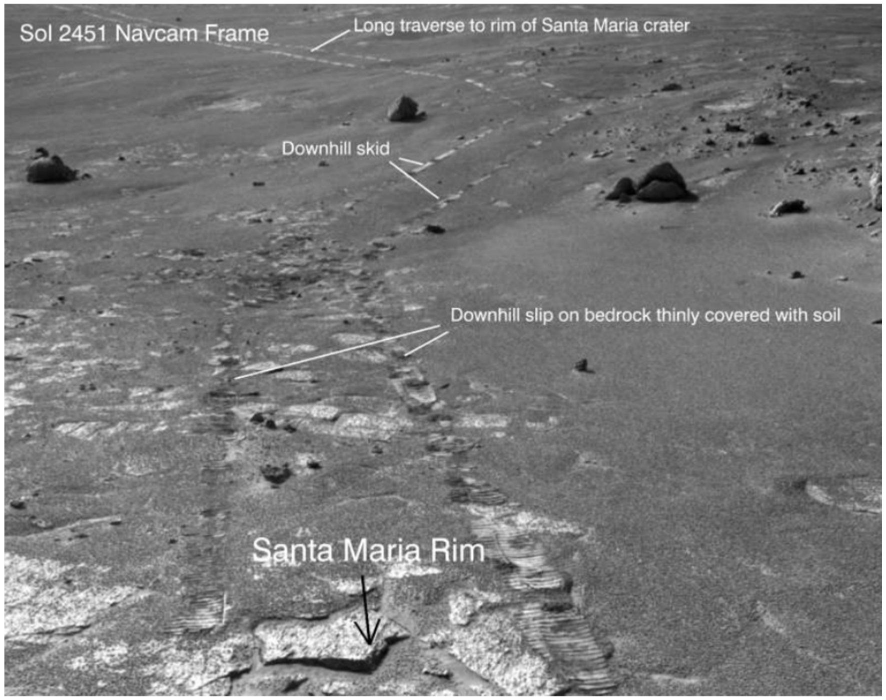



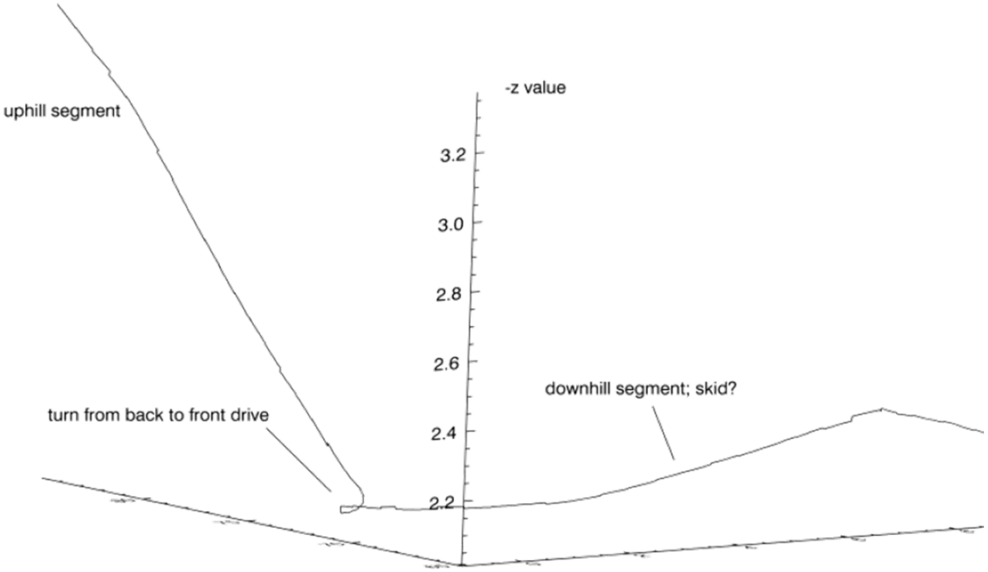



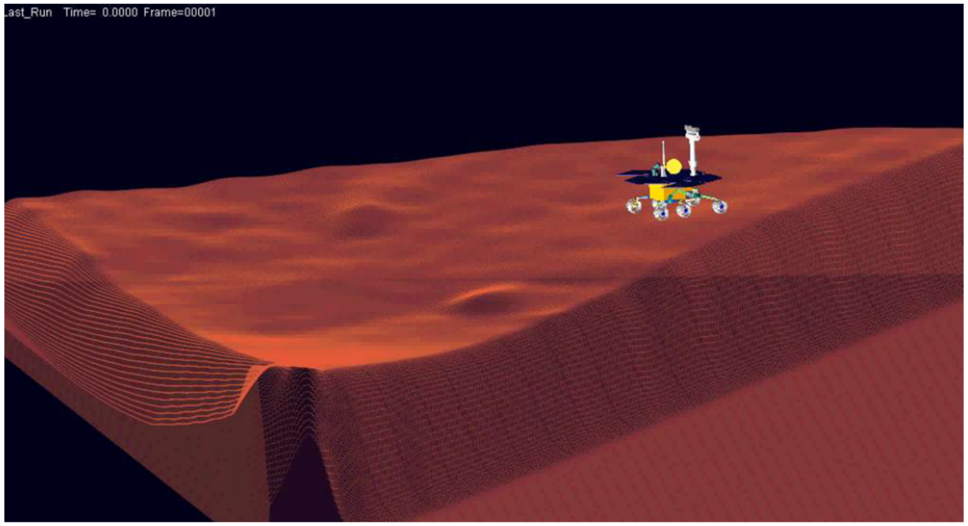


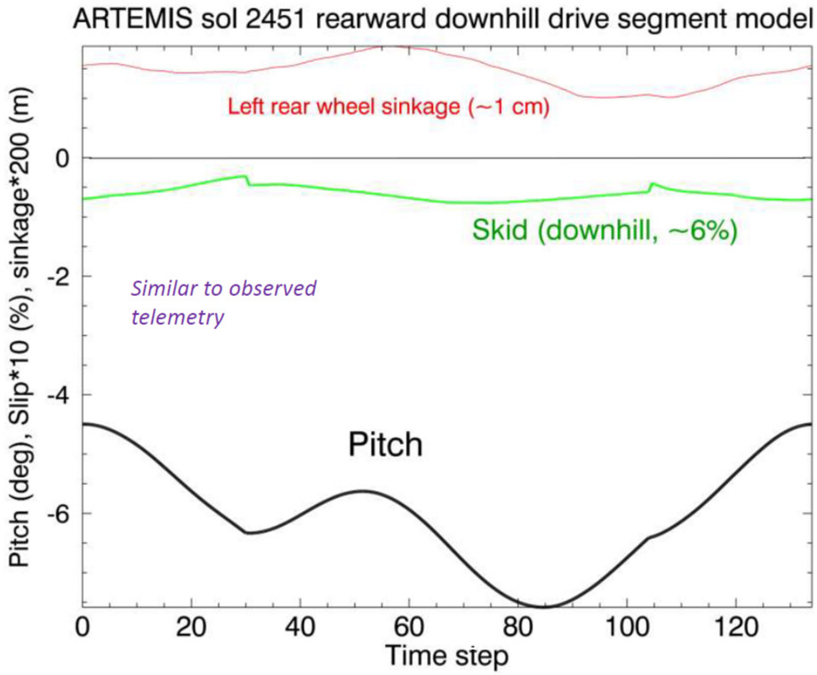
MSC Software

# Santa Maria Downhill Skid

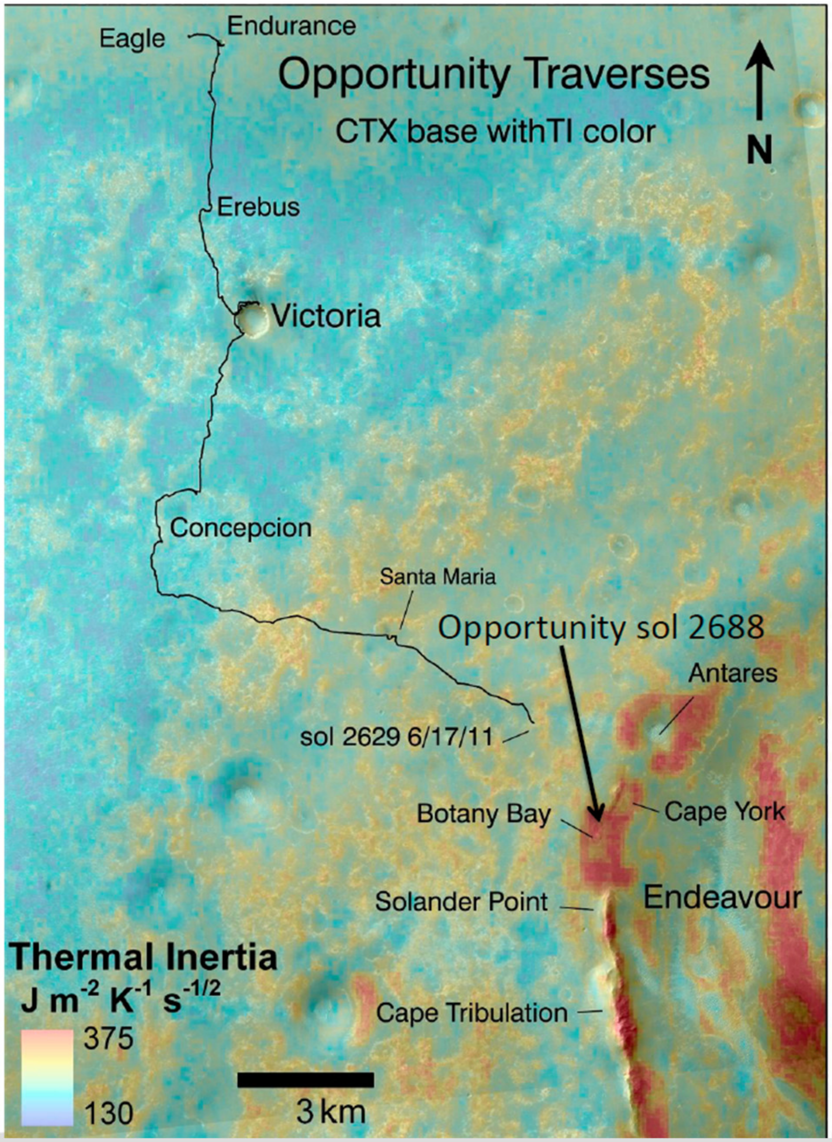


# Arrival at Endeavor




## Spirit Point, Cape York, Endeavour

- Thermal Inertia (TI) over CTX mosaic showing Opportunity's traverses
- TI values similar to Gusev plains and Columbia Hills
- Botany Bay based on HiRISE has extensive bedrock exposed
- Cape York has CRISM-based spectral signature similar to slightly altered basaltic sand (perhaps small smectite exposures)
- Implies relatively easy traversing across Botany Bay and Husband Hill-like mobility on Cape York
- Thermal inertia from Mike Mellon and traverses from Ron Li and OSU Team

2

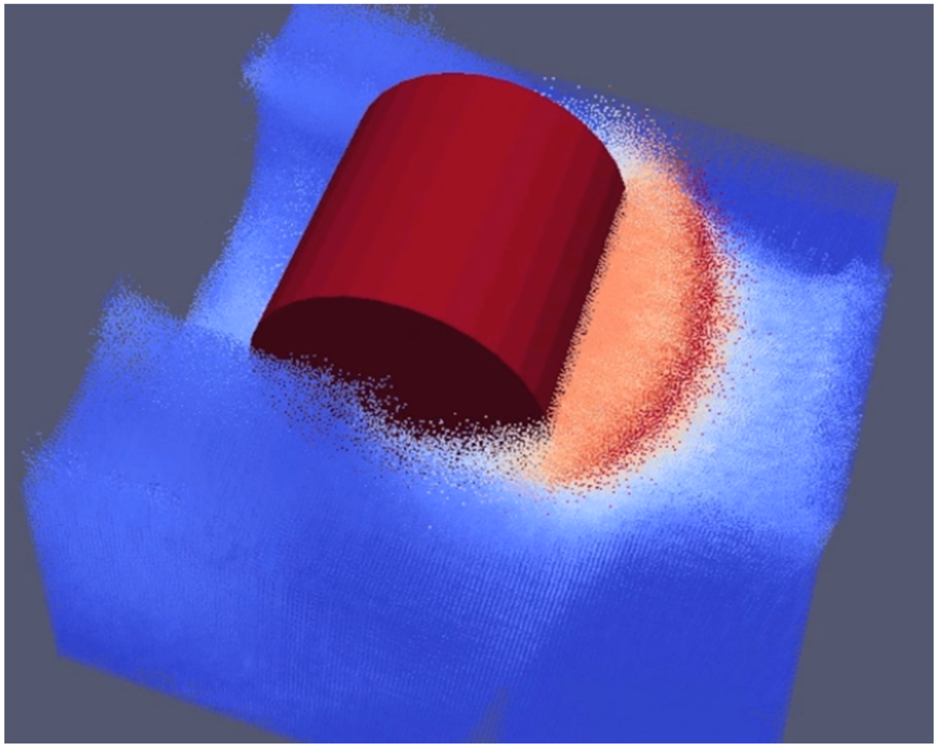
Animation using HiRISE over HiRISE based DEM
DEM courtesy Ron Li, OSU
with 10X VE



(SOL = Mars DAY)

# Challenges and Future Work

- DEM's
- Better Reduced-order Models
- Dynamic Terramechanics
- Deformed-soil Formulation
  - Multi-pass Simulation
  - Enhanced Soil Damping
- N+1 scientific instrument



DEM's demo by R. Mukherjee at JPL.
Work sponsored by DARPA.

1.7M particles
3 hours on 100 processors

# Thank You, Q&A?

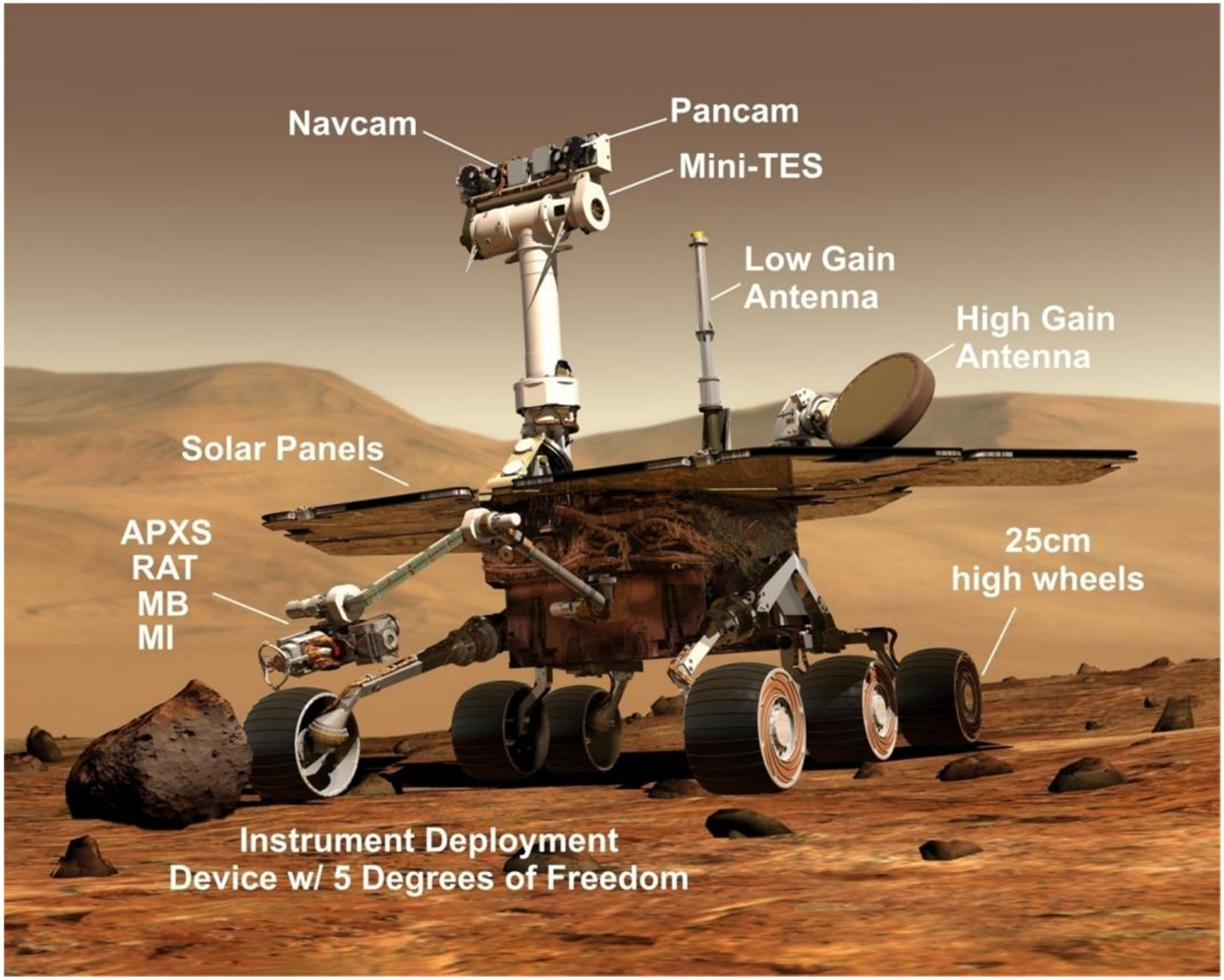
NASA's Mars Science Laboratory (MSL) Design/Test Model (DTM) in the sandy Mars Yard at JPL

**Brian Trease, NASA JPL**
**Mars Rover Mission**
**xTerramechanics**

- brian.p.trease@jpl.nasa.gov
- http://marsrover.nasa.gov/
- http://www.kiss.caltech.edu/study/xterramechanics/

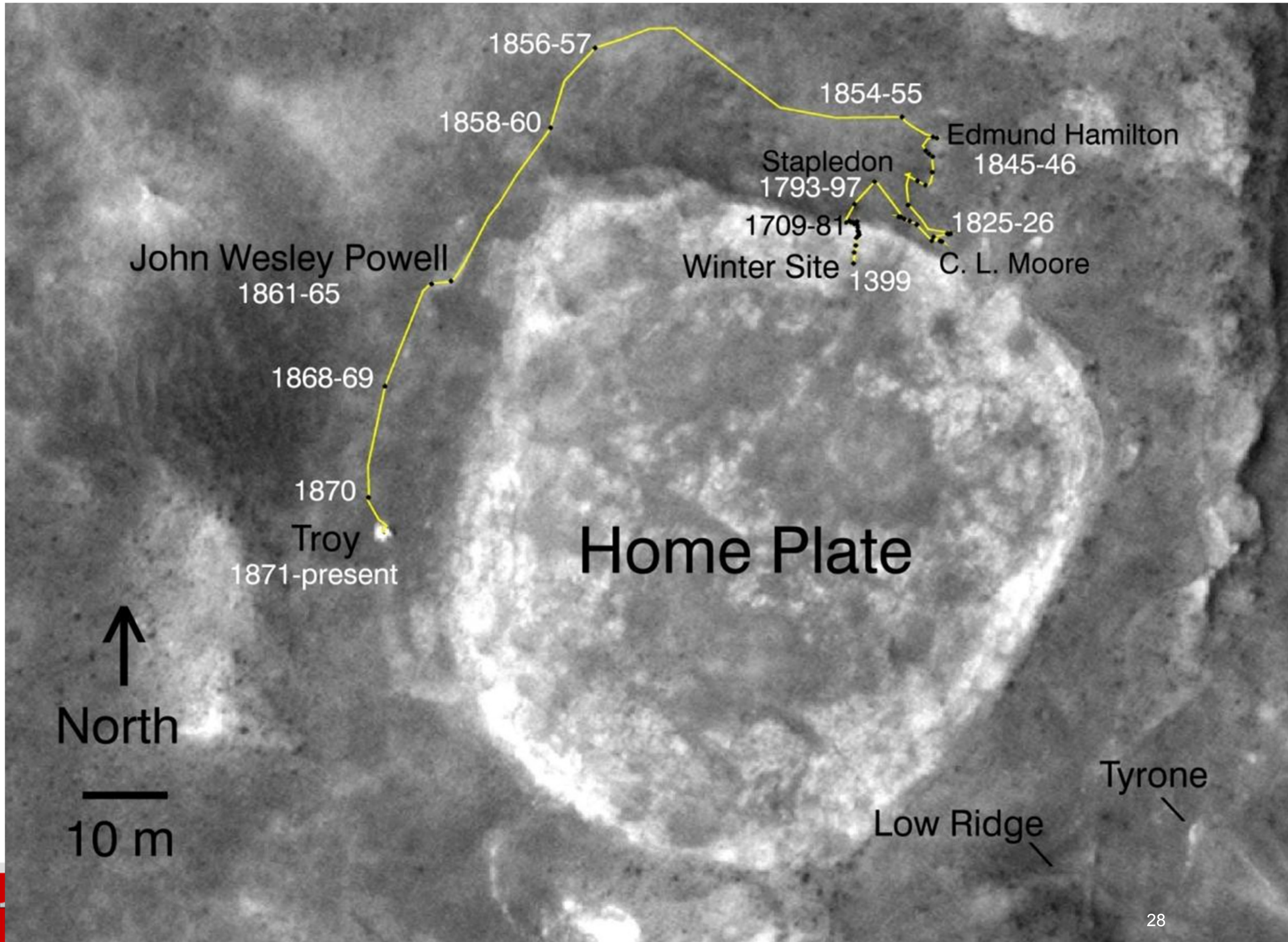
# APPENDIX and EXTRA SLIDES

# Spirit Rover

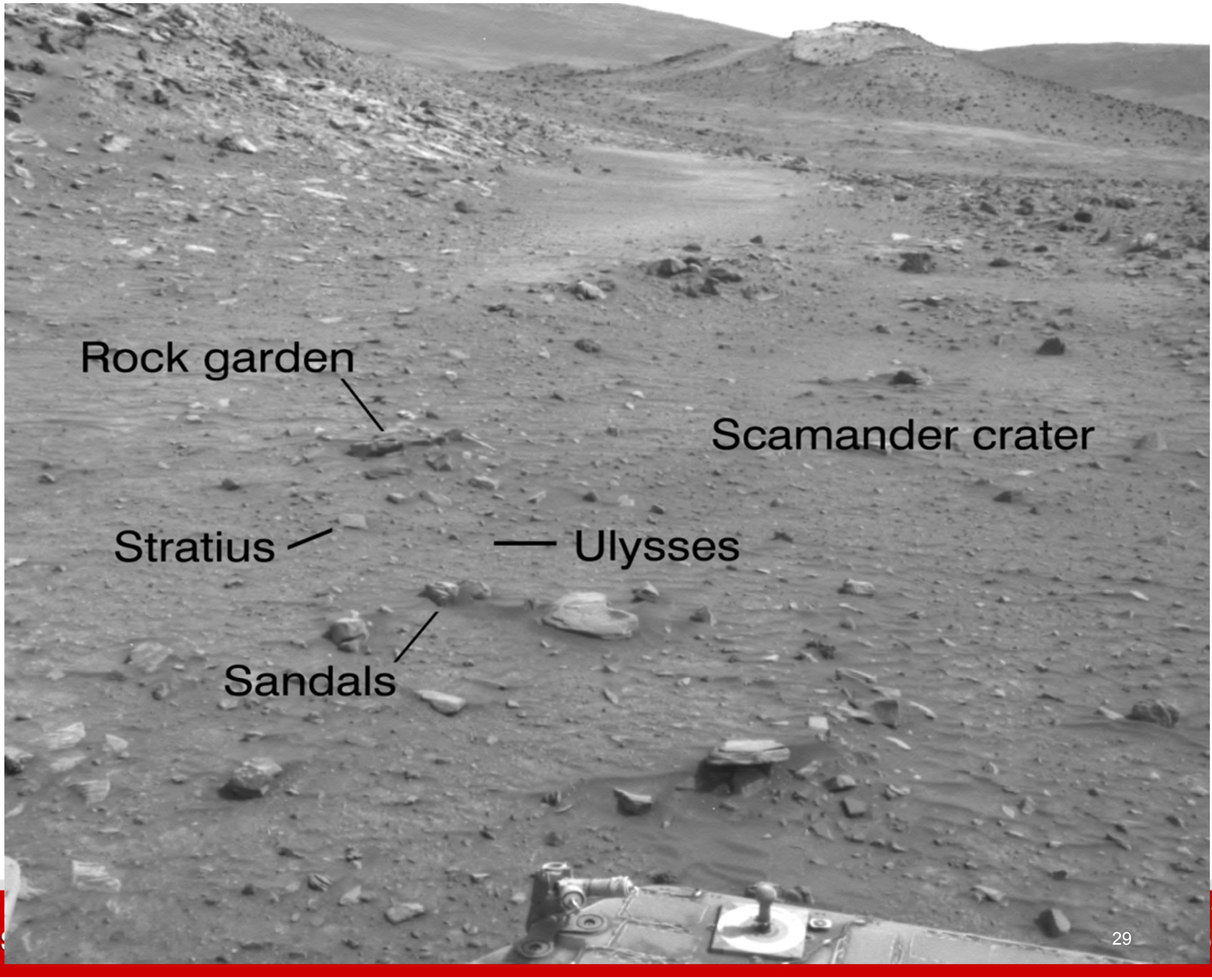



- Right front wheel drive actuator failed on sol 779
- Embedded in sands of Troy after breaking through soil crust
- Extrication stopped Sol 2169 to prepare for winter
- Last communication March 2010

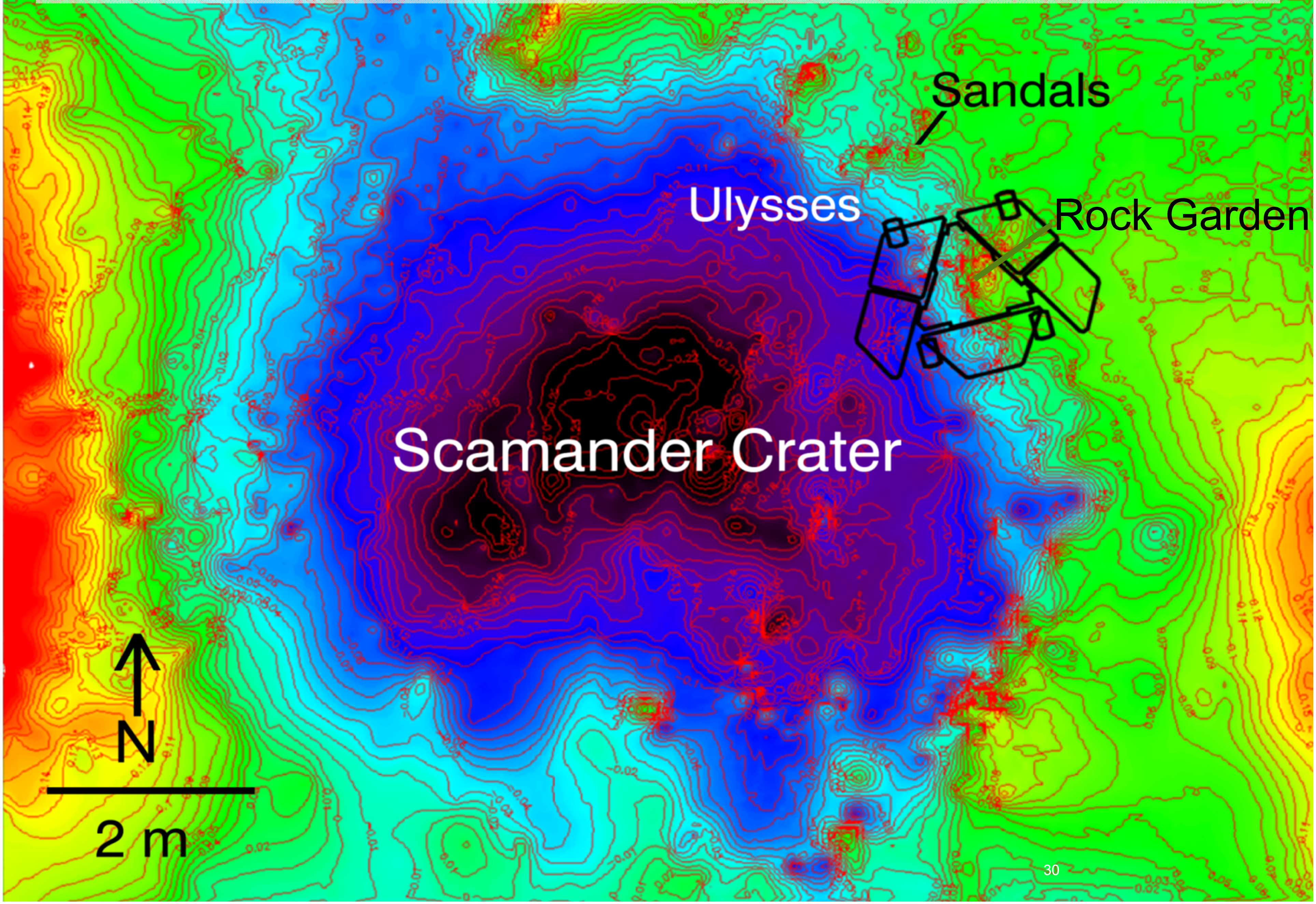
# Spirit's Traverses Since Leaving the Third Winter Site

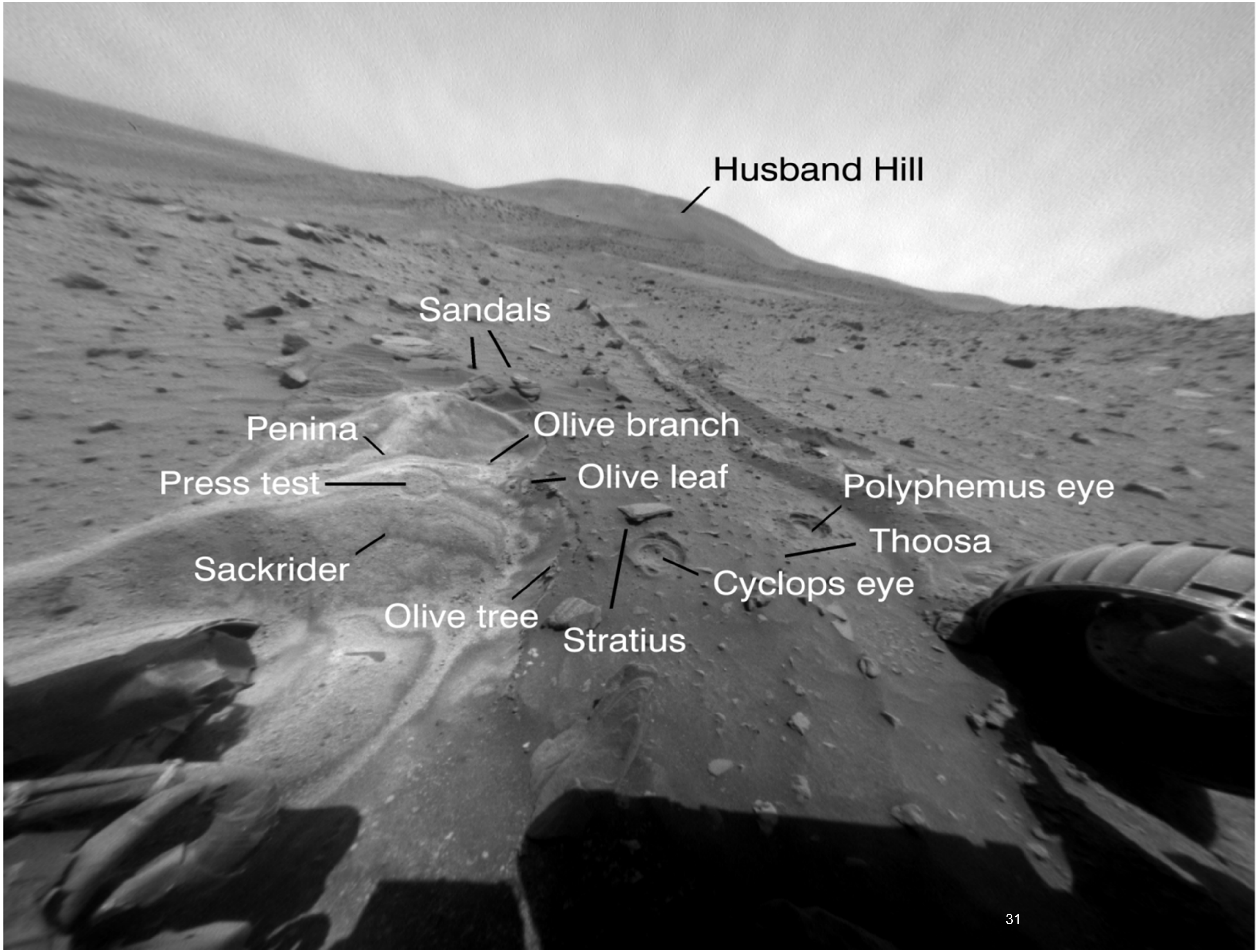


# Troy Region as Seen on Sol 1870



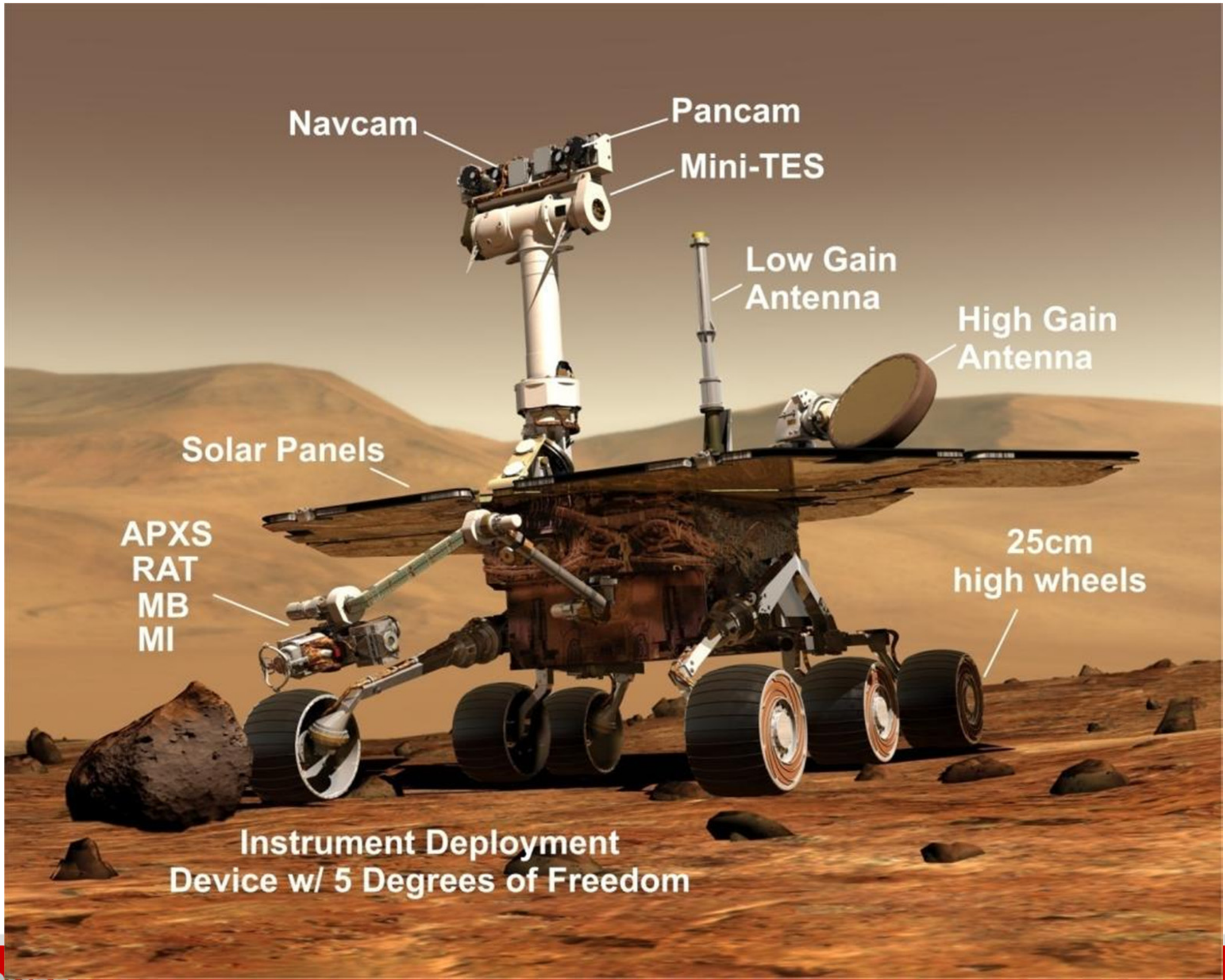
# Scamander crater 8 m wide and 25 cm deep



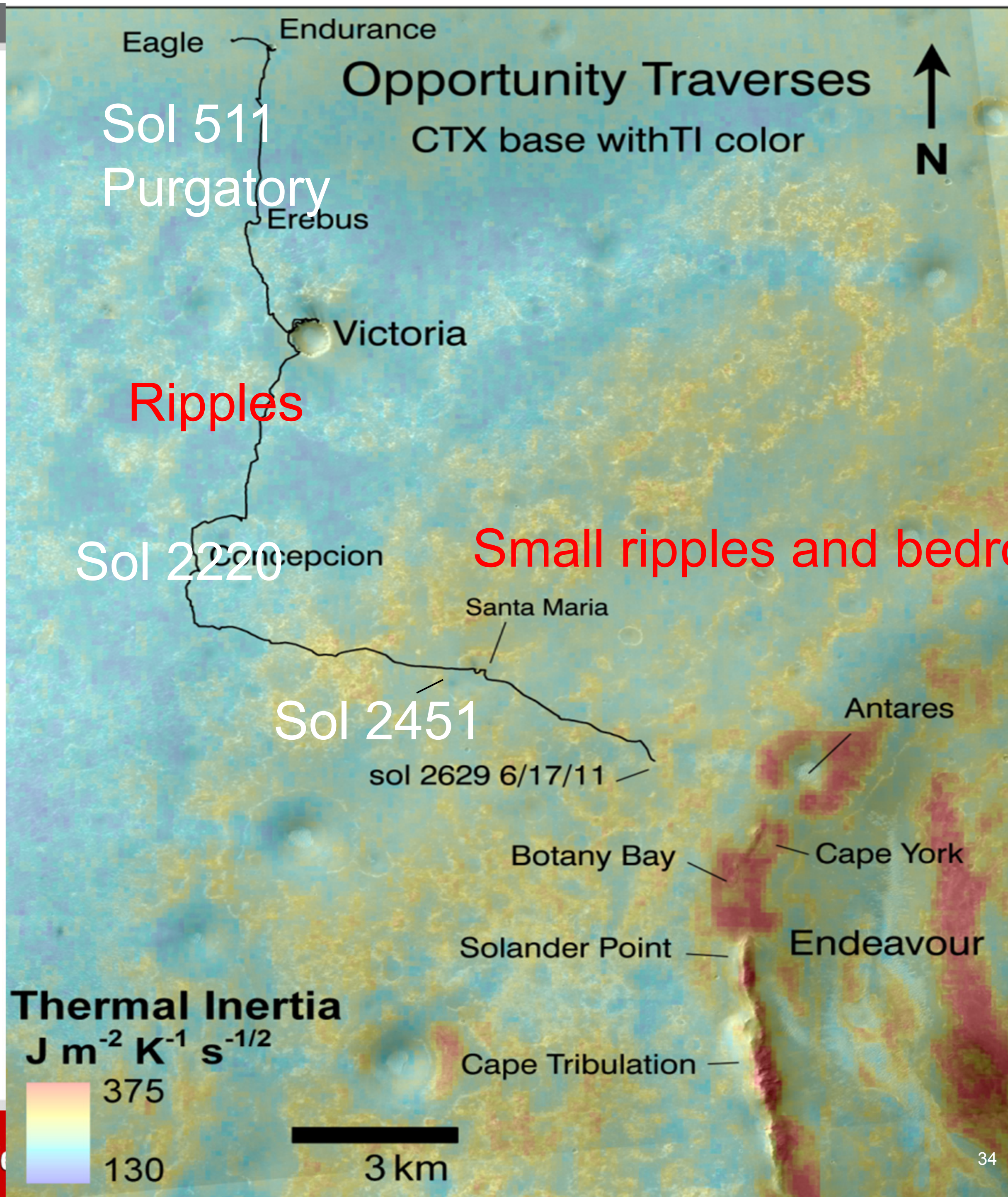

Husband Hill
Sandals
Penina
Olive branch
Press test
Olive leaf
Polyphemus eye
Thoosa
Sackrider
Cyclops eye
Olive tree
Stratius

## “Breast Stroke” Maneuver Moves Spirit ~35 cm over last drives

# Opportunity Rover

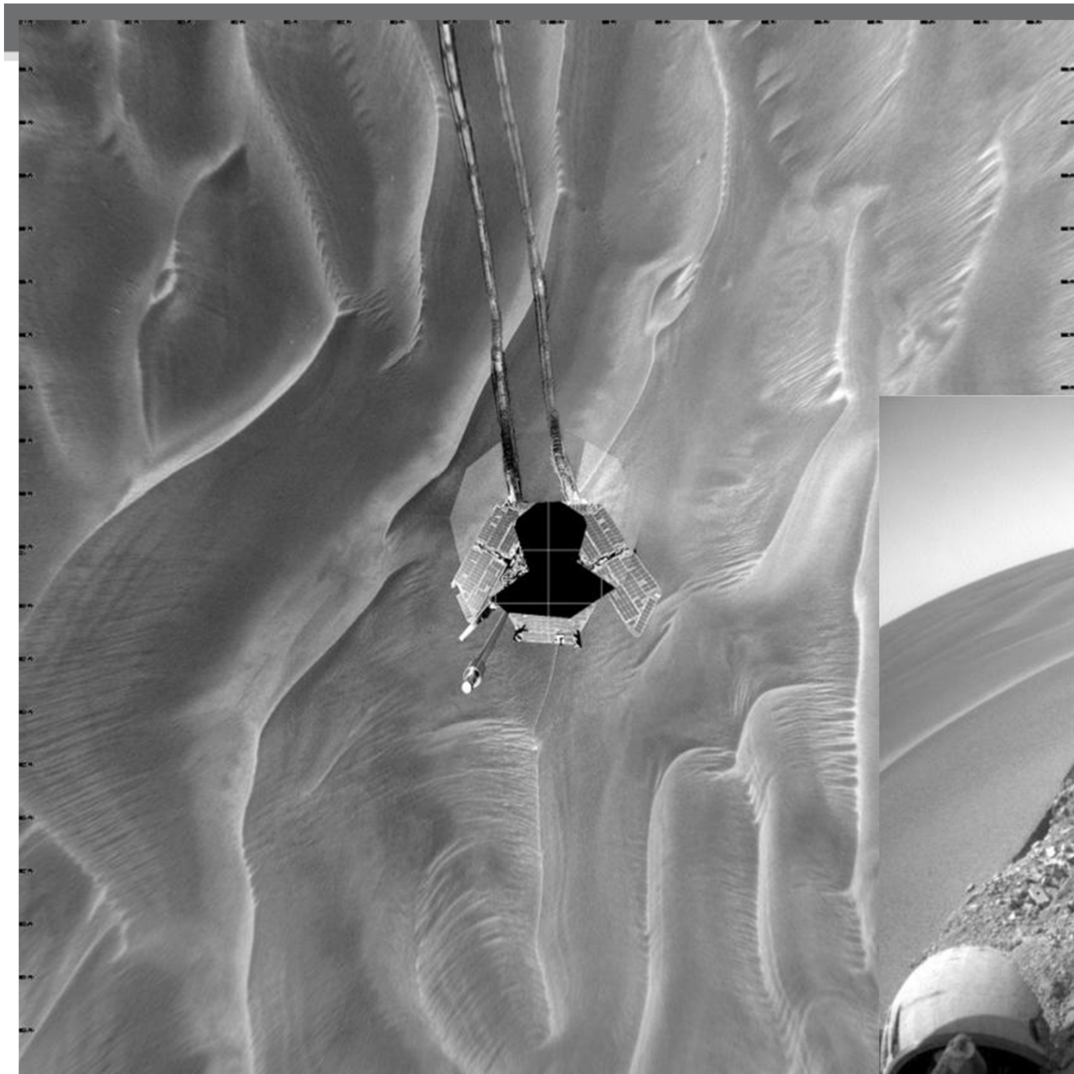



- Right front wheel left rotated ~8 deg inward when azimuthal actuator failed
- Shoulder IDD actuator failed
- Mini-TES no longer responding

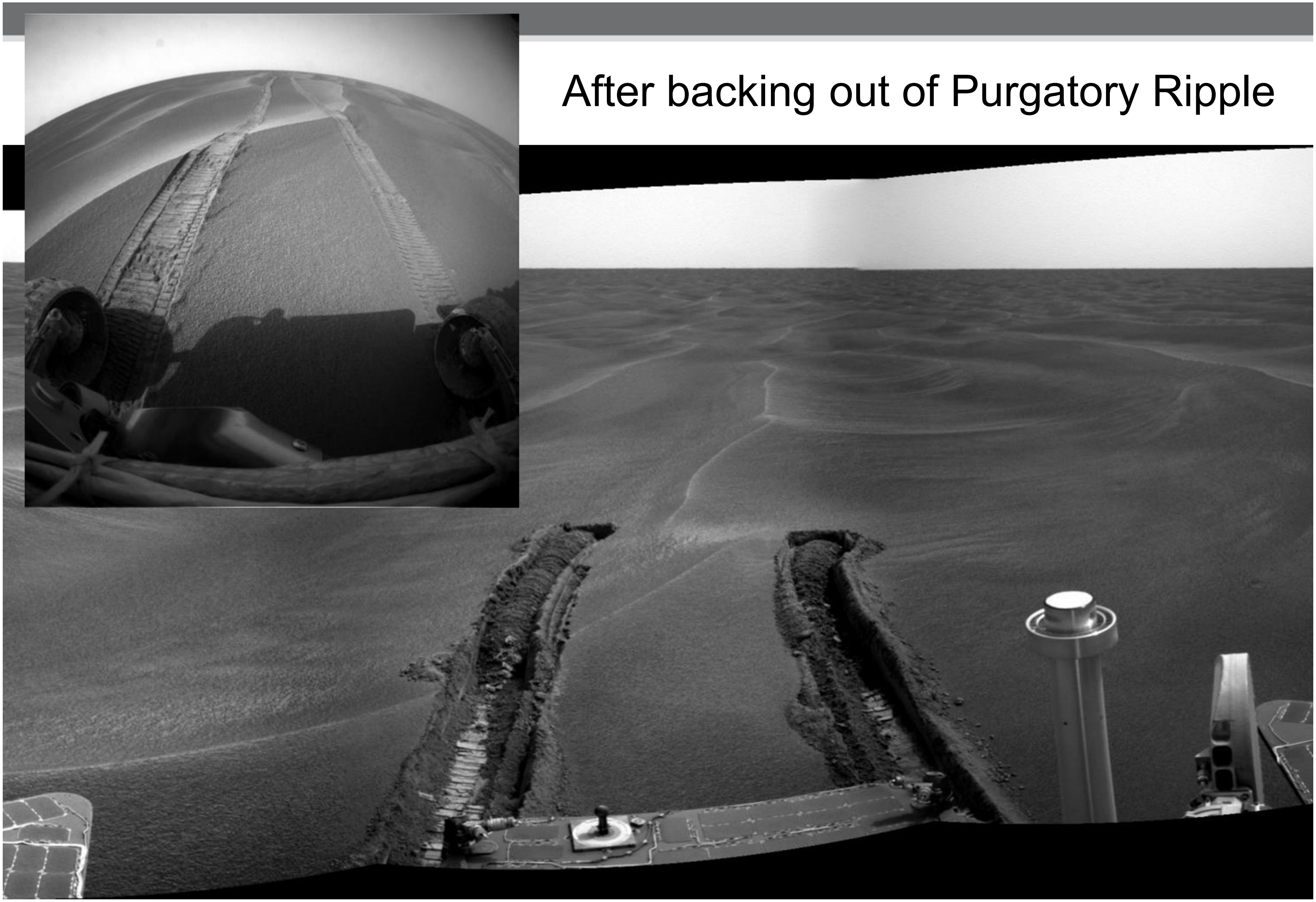


Opportunity Traverses
CTX base withTI color
N
Eagle
Endurance
Sol 511
Purgatory
Erebus
Victoria
Ripples
Sol 2220
Concepcion
Small ripples and bedrock
Santa Maria
Sol 2451
sol 2629 6/17/11
Antares
Botany Bay
Cape York
Solander Point
Endeavour
Cape Tribulation
Thermal Inertia
J m-2 K-1 s-1/2
375
130
3 km

# Purgatory Ripple



# After backing out of Purgatory Ripple



# Rover Mobility

- All rover missions require robots to travel over challenging terrain
  - Highly deformable
  - Sloped
  - Rocky
- Understanding rover-surface interaction very important
- “Terramechanics” is study of vehicle-terrain interaction

# More Equations

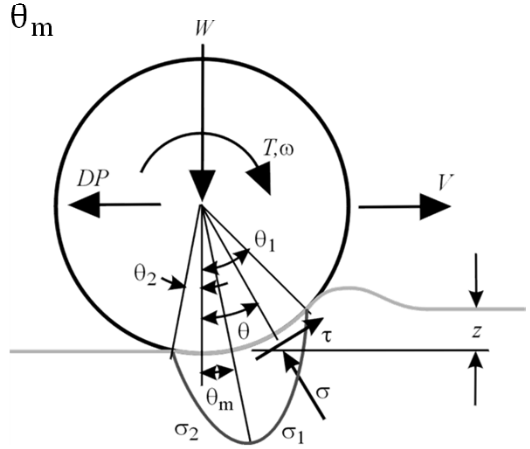
## NORMAL STRESS DISTRIBUTION

$$\sigma = \begin{cases} \sigma_1 = \left(\frac{k_c}{b} + k_\phi\right) z_1^n & \theta_m < \theta < \theta_f \\ \sigma_2 = \left(\frac{k_c}{b} + k_\phi\right) z_2^n & \theta_r < \theta < \theta_m \end{cases}$$

$$z_1 = r\,(\cos\theta - \cos\theta_f)$$

$$z_2 = r\left(\cos\left(\theta_f - \frac{\theta - \theta_r}{\theta_m - \theta_r}(\theta_f - \theta_m)\right) - \cos\theta_f\right)$$

$$\theta_m = (a_1 + a_2 i)\theta_f$$

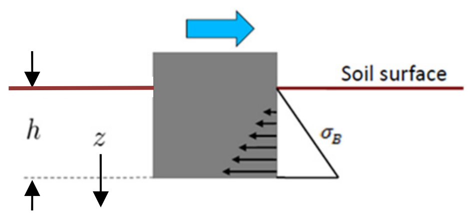



## LATERAL FORCE (COMPACTION)

$$F_u = br\int_{\theta_r}^{\theta_f} (c + \sigma(\theta)\tan\theta)\left(1 - e^{-\frac{j_y}{k_y}}\right) d\theta$$

## LATERAL FORCE (BULLDOZING)

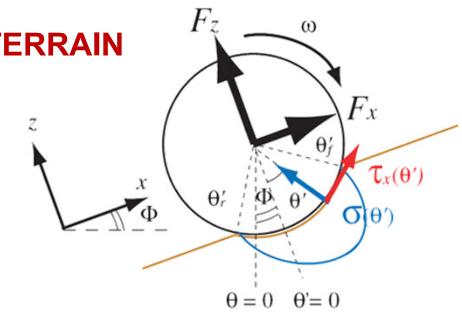
$$\sigma_B = \gamma z N_\gamma + cN_c + qN_q$$

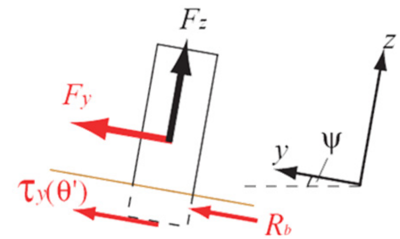



$$N_\gamma = \frac{2\left(N_q + 1\right)\tan\phi}{1 + 0.4\ \sin 4\phi} \quad N_c = \frac{N_q - 1}{\tan\phi} \quad N_q = \frac{e^{(1.5\pi - \phi)\tan\phi}}{2\cos^2(\pi/4 + \phi/2)}$$

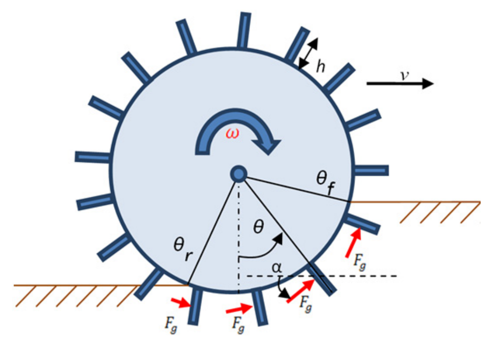
$$F_b = \int_{-r\sin\theta_f}^{r\sin\theta_f} [\gamma N_\gamma f(x) + cN_c + qN_q] f(x)dx$$

## TILTED TERRAIN




FREE-BODY DIAGRAM FOR GENERALIZED WHEEL WITH TILT. FIGURES ARE FROM ISHIGAMI




$$F_g = b\left[\frac{1}{2}\gamma h_g^2 N_\phi + 2ch_g\sqrt{N_\phi}\right]\cos\alpha$$

## GROUSER (CLEAT) THRUST EFFECT

# Explicit Force Calculations