Earth-Science Reviews 134 (2014) 16–69

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

The behaviour of deformable and non-deformable inclusions in viscous flow

Fernando O. Marques [a,*], Nibir Mandal [b], Rui Taborda [c], José V. Antunes [d], Santanu Bose [e]

[a] University of Lisbon, Lisboa, Portugal
[b] University of Jadavpur, Kolkata, India
[c] University of Lisbon and IDL, Lisboa, Portugal
[d] University of Lisbon, Applied Dynamics Laboratory, Instituto Superior Técnico, Campus Tecnológico e Nuclear de Sacavém, Portugal
[e] University of Calcutta, Kolkata, India

A R T I C L E I N F O

Article history:
Received 29 October 2012
Accepted 8 March 2014
Available online 27 March 2014

Keywords:
Simple and pure shears
Inclusion rotation
Confinement
Slip
Shape preferred orientation
Experimental analogue
Analytical and numerical modelling
Matrix rheology

A B S T R A C T

Many are the situations in Geology in which non-deformable and deformable inclusions are carried about in suspension by the motion of a fluid, or a rock behaving like a fluid. Therefore, it is of crucial importance to Geosciences to understand the rotational behaviour of inclusions in viscous flow, and the effects in the matrix deformation. A major step was given by Jeffery (1922), who provided approximate analytical solutions that have been extensively used to describe how rigid spheroids rotate in homogeneous flows. He considered isolated inclusions in no-slip contact with an infinite width matrix. However, in a great variety of geological processes, flow can be confined, the inclusion can deform, the inclusion/matrix interface can be slipping, or inclusions can interact with neighbours. By analytical, experimental analogue, and numerical modelling it has been shown how inclusions rotate, how the surrounding matrix flows, how pressure and velocity control rigid inclusion behaviour, and how the models can be applied to geological processes. Modelling has shown that: (1) for wide channels (ratio W_r of channel width over inclusion least axis length >10) and non-slipping interface, results agree with Jeffery's model, while for narrow channels ($W_r < 5$) or slipping interface the results deviate greatly from Jeffery's model. (2) For narrow channels or slipping interface, inclusions with aspect ratio A_r (greatest over least principle axis) >1 can rotate backwards (antithetic rotation, against flow vorticity) from an initial orientation $\phi = 0°$ (greatest principle axis parallel to the shear plane), in great contrast to Jeffery's model. (3) Back rotation is limited because inclusions reach a stable equilibrium orientation (ϕ_{se}) at shallow positive angles ($0° \le \phi < 90°$). (4) There is also an unstable equilibrium orientation (ϕ_{ue}), which defines an antithetic rotation field with ϕ_{se}, and both ϕ_{se} and ϕ_{ue} depend on confinement and inclusion aspect ratio and shape. (5) The flow around rigid inclusions is greatly perturbed by confinement or slipping interface, and a new flow pattern (cat eyes-shaped) has been described. (6) The numerical models provide detailed and coherent information about the physical parameters involved in the process (e.g. pressure and velocity distributions within the model), which helps to explain inclusion behaviour. (7) The existing models can be used to quantify important parameters that characterise ductile shear zones.

Contents

* Corresponding author. Tel.: +351 217500000; fax: +351 217500064.
E-mail address: fomarques@fc.ul.pt (F.O. Marques).

http://dx.doi.org/10.1016/j.earscirev.2014.03.007

1. Introduction

1.1. Rationale

A wide variety of geological materials such as rocks, magmas and glaciers show a composite behaviour due to the presence of mechanically contrasting objects suspended in a continuous ductile matrix. Therefore, the investigation of the kinematic behaviour of inclusions in viscous flow is a fundamental step towards the understanding of the basic physics of such inclusion–matrix composites, hence of many geological processes. The ductile matrix behaves macroscopically as a viscous fluid in many situations, and the viscosity can vary widely in geological materials. The common low-viscosity fluids are air, liquid water and magma (especially silica-poor, flowing through the lithosphere or as lava flows at the Earth's surface). In contrast, rocks and glaciers can behave as high-viscosity fluids under geological conditions, and their viscosities are many orders of magnitude higher than those of water or magma. All these low- or high-viscosity fluids carry rigid or deformable inclusions in suspension, and the suspended materials can rotate and affect the rheology of the enclosing medium during flow (e.g. Einstein, 1906). Therefore, the understanding of the rotational behaviour of inclusions in the flowing matrix and of the bulk rheology of