layer, defining two decks of structures of contrasting wavelengths and styles (e.g., thick upper Paleozoic sandstones above thick shale units in the frontal Ouachitas). Such differences are recognized regionally; however, examples of local along- and across-strike changes in structural style suggest abrupt changes in mechanical stratigraphy.

The Southwest Montana transverse zone marks a dextral offset in the north-striking Cordilleran thrust front and an abrupt along-strike change in structural style. South of the transverse zone, a carbonate-dominated Cambrian succession overlies crystalline basement rocks and is imbricated in west-dipping thrust sheets. North of the transverse zone, north of a large basement fault at the south boundary of the Precambrian Belt sedimentary basin, the Cambrian succession is deformed by variably steep, short-wavelength folds and variably dipping, generally steep faults above a décollement in the thick Belt clastic succession.

In the Appalachian thrust belt in Alabama, the basal detachment is in Cambrian shale, and large listric frontal ramps are controlled by a Cambrian-Ordovician massive carbonate stiff layer. Several large trailing synclines, however, end abruptly along strike in steep plunge at lateral ramps. Structural relief of the plunge corresponds to thick, disharmonic duplexes (mushwads) of weak Cambrian shale beneath the stiff layer. Variations in original sedimentary thickness of the Cambrian shales reflect synsedimentary basement faults that are now beneath the allochthon. The mushwads evidently nucleate in sedimentologically thicker weak-layer shales and distort the overlying stiff layer.

9:15 AM Shaw, John H.

PATTERNS OF IMBRICATE THRUSTING

SHAW, John H., Dept. of Earth & Planetary Sciences, Harvard University, 20 Oxford St., Cambridge, MA 02138; BILOTTI, Frank D., and BRENNAN, Peter A., Texaco EPTD, 3901 Briarpark, Houston, Texas 77042

We describe patterns of imbricate thrusting and related folding using seismic reflection profiles, stereoscopic satellite imagery, and balanced kinematic models. Diagnostic patterns of imbricate structures in cross section, including multiple dip domains in fold limbs and refolded thrust faults, are used to interpret imbricate geometries and to infer thrusting sequences. Measures of folding shear strains are employed to identify break-forward systems in which younger and deeper faults refold overlying structure. In contrast, break-backward sequences with younger and shallower thrusts form a wide range of viable geometries that are not expected to conserve these folding strains. Thus measures of folding shear strains are used to infer thrusting sequences and constrain kinematically viable structural interpretations. We also use multispectral satellite imagery, including stereoscopic data, to identify map-view patterns of imbricate structures that are also imaged by high-quality seismic reflection profiles. In an example from the Peruvian Andes, we suggest that apparently conflicting patterns of simple break-forward and break-backward thrusts are explained by coeval fault motions. These methods of recognizing and interpreting patterns of imbricate thrusting provide new tools for understanding the deformation histories of fold-and-thrust belts, including the definition of complex structural closures with opportunities for hydrocarbon reservoir duplication.

9:30 AM Washington, Paul A.

EFFECTS OF EUSTATIC EVENTS ON THE INTERACTION BETWEEN FORELAND THRUST PATTERNS AND ASSOCIATED FORELAND BASIN DEPOSITION

WASHINGTON, Paul A., Dept. of Geosciences, Northeast Louisiana Univ., Monroe, LA 71209, gewashington@alpha.nlu.edu

The areal controls on depocenters within the foreland basin by coeval thrusting and folding within the adjacent orogen is well established. Mechanical models of thrust belt evolution indicate that there should also be a strong control of thrust belt evolution (including location, spacing, and geometry of the thrust surfaces) by the areal distribution and surface morphology of the coeval foreland basin deposition. Thus, there is a kinematic feedback loop between a foreland basin and the structural evolution of the adjoining orogen, but the resulting relationships between the thrust belt geometries and the accompanying foreland depositional systems are generally readily interpreted.

The introduction of eustacy into the feedback loop between foreland deposition and thrusting results in a series of transitional geometries between differing types of basin. Because the proximity of the shoreline to the thrust front strongly influences the surface morphology of the proximal basin surface, which, in turn, controls the location of future thrust ramps, changes in the location of the shoreline relative to the thrust front dramatically effect the location of, and even the potential for, new ramp nucleation and growth. This not only influences sheet length and the areal shapes of the next generation of thrust sheets, it also can change the amount of displacement that occurs on the existing faults before the next thrust fault forms, and it can change the areal relations between existing ramp offsets/terminations and future ramp nucleation. These changes have dramatic consequences for the delivery of sediment to the foreland basin from the orogen, and so should strongly influence the stratigraphic architecture of the foreland basin.

The effects of eustacy on common thrust belt - foreland basin relations will be discussed, and models will be developed showing the specific depositional and stratigraphic consequences of eustatic events on these systems.

9:45 AM Hayman, Nicholas W.

THE ROLE OF PRE-THRUST NORMAL FAULTS ON THRUST SYSTEM DEVELOPMENT: EXAMPLES FROM THE CHAMPLAIN THRUST SYSTEM, WEST-CENTRAL VERMONT

Hayman, Nicholas W., Dept. of Geological Sciences, University of Washington, Seattle, WA. 98195; **Kidd**, William S.F., Dept. of Earth and Atmospheric Sciences, University at Albany, NY 12222

Normal faults which pre-date tectonic transport of allochthonous and par-autochthonous rocks along thrust faults are widely recognized in the forelands of mountain belts. New geologic maps of the Ordovician Champlain Thrust System, in the shelf-facies rocks of west-central Vermont, show that such pre-thrust normal faults played a role in the development of the thrust system geometry. Throughout the north-south striking Champlain Thrust System are a set of across-strike normal faults. These function as sharp lateral ramps in the thrust faults and contribute to changes in the stratigraphic level of thrusts from north to south. These changes in stratigraphic level in most cases cannot be accounted for purely by syn-thrust lateral ramps. The across-strike faults are thus interpreted to be a pre-thrust generation of trench-normal, normal faults. They are subsidiary to the set of along strike, trench parallel, normal faults which would be predicted by models of normal faulting in response to lithospheric flexure with the onset of collision. The Champlain Thrust System is bound to the east by a late, to post- orogenic normal fault. East of this late normal fault is the western extent of the Taconic Allochthon: continental rise facies slates and arenites, tectonically transported over a belt of mixed shales, slates, and melange. East of this allochthon is a belt of carbonate rocks, correlative to the rocks in the Champlain Thrust System. Though their emplacement above the westernmost allochthon is facilitated by the Taconic Frontal Thrust, an out-of sequence Taconic-type thrust, it is proposed that these carbonates were initially brought to a topographically higher position on the shelf by trench-parallel normal faults having significant amounts of throw. With the latter stages of tectonic transport, thrusts related to the Taconic Frontal Thrust cut through this higher belt of carbonates and emplaced it to the east of, and structurally above, the Champlain Thrust System. In summary, pre-thrust normal faults, usually interpreted to be buried beneath the basal thrust(s), can play a role in local thrust system development by acting as nucleation sites for lateral ramps, ramps of thrusts, and can lead to the placement of rocks in structurally higher positions than their inboard equivalents. In addition, pre-thrust stratigraphic offset can lead to regional changes in the structural level of thrusts, as well as making balancing of cross-sections difficult.

10:00 AM Ahmad, Imtiaz

BASEMENT-COVER DECOLLEMENT, BASEMENT DUPLEXES AND NORMAL FAULTS ON THE EDGE OF A SUTURE ZONE, LOWER SWAT, NW HIMALAYA, PAKISTAN.

AHMAD, Imtiaz*, (ahmad@epoch.geol.sc.edu); Dennis, A.J., Geol.USC, Aiken, SC 29801-6309, and Shervai, J.W.*., *Geological Sciences, USC, Columbia, SC, 29208.

Indian-plate basement massifs south of the Main Mantle Thrust (MMT) in Lower Swat, Pakistan, are uplifted basement-cored duplexes framed by large normal and tear faults. The high grade (600°C/10kb) putative cover (Alpurai group metasedimentary rocks) is detached from well-known granitic massifs (Swat gneisses) at Ilam and Dopialo domes, along variably deformed tourmaline granite gneiss sheets that range from undeformed to strongly lineated mylonites. For hundreds of meters away from the tourmaline orthogneiss, Swat gneisses show evidence of extreme ductility, e.g. plastic deformation of augen, strong lineation, and are "tourmaline-corrupted". Kinematic indicators show the most recent ductile motion was to the east on the eastern sides of the domes, and to the west on the western side of the domes. We interpret that doming of Swat gneisses caused the Alpurai group to be shed off the flanks of the rising dome.

The faults bounding horses of Swat gneisses define a N-S striking duplex, ca. 2kmx4km (strike length), of Manglaur 'fm.' The Manglaur thrust zone is complex interleaving of all cover sequence rock types and granitic gneisses, rather than a single country rock (Manglaur fm) into which Swat is intruded. The floor thrust of the duplex is nowhere exposed, while the MMT marks the roof thrust. We interpret several blind thrusts within the gneisses, to the west of the duplex. Absence of a basal conglomerate, highly variable thickness in the lower Alpurai group, and absence of amphibolite sills from Swat gneisses, which locally make up to one-third of the cover sequence, indicate that Alpurai group is faulted against Swat gneisses, rather than unconformably deposited on them.

In the south, Alpurai group is juxtaposed against weakly metamorphosed Swabi terrane (Late Proterozoic Gandaf Fm to Triassic Nikanai Ghar Fm), along a south dipping normal fault (Nikanai Ghar fault). The Indian-plate basement massifs south of the MMT in Nanga Parbat, Kaghan, Hazara, and Besham, and continuing east of NP, are probably exposed by similar mechanisms.

10:15 AM Fakhari, Mohammad

ROLE OF STRATIGRAPHY ON CREATION OF THE MAJOR FAULTS AND VARIATION OF FOLDING STYLES ON THE ZAGROSS RANGE SOUTH WEST IRAN

FAKHARI, Mohammad, Geology Dept. Exploration, NIOC, POBox 1065 Tehran Iran.

Major strike slip tear faults of Kazeroon, Mengarak, Izeh, Sepidan and Sarvestan in the folded belt of Zagross has been reported as basement faults during last 50 years.

Recent structural and stratigraphic investigations based on detail lithological study of Phanerozoic sedimentary sequence and geometrical analysis of the anticlinal structures reveal that these faults appears on the major stratigraphic variation borders. This is due to different folding styles caused by changing in the thickness of competent group of sedimentary sequence at either sides of the border.

During the folding process the greater folds with larger wavelength and higher amplitude in more competent side of the border, in contrast with the small folds of the other side, developes extra shear stresses and bounded tear faults. This idea is supported by the displacement decrease towards the either ends of the Kazeroon, Mengarak and Izeh faults. This also tends to no basement fault engagement in the creation of the Zagross major tear faults. Vanishing of these faults below the sedimentary sequence and wholeness of the basement, also have been proved by investigation of the confirmed depth of shallow earthquake epicenters during the last 15 years, recorded by the local stations.

10:30 AM Camerlo, Rion H.

GEOMETRY AND KINEMATIC EVOLUTION OF DETACHMENT FOLDS: MONTERREY SALIENT, SIERRA MADRE ORIENTAL, MEXICO

CAMERLO, Rion H., and MARRETT, Randall A., Department of Geological Sciences, The University of Texas at Austin, Austin TX 78712, camerlo@mail.utexas.edu

The Monterrey Salient is a regional salient that protrudes northward from the Laramide-age deformation front between Saltillo and Linares, Mexico. Structural style within the Monterrey Salient is dominated by 5-10 km wavelength detachment folds with structural reliefs of 2-3 km. Many kinematically distinct models have been proposed for detachment fold development. The applicability of the models to two anticlines--San Juan Bautista (SJB)and San Blas(SB)--in the Monterrey Salient was studied through analysis of fold geometry and strain mechanisms.

A geometric survey of both anticlines using differential GPS equipment revealed that the anticlines have chevron-shaped tops rather than the flat tops of 'box-folds' reported for the region. In cross section the hinge widths of both folds are much smaller than the limb lengths giving both folds angular shapes. SJB anticline verges toward the hinterland and SB anticline is upright. Anisotropy of Magnetic Susceptibility studies indicate that the units within the folds have developed pronounced tectonic fabrics. The strain mechanisms that developed these fabrics were partitioned as a function of lithology. Significant distributed shearing occurred in limestone units through both pressure solution and calcite twinning, displacing original diagenetic stylolite teeth tops toward anticline crests. More pelagic limestones underwent greater pressure solution. Dolostone units are densely fractured and imbricated by minor thrusts verging toward anticline crests. Extension fracture development is dominated by axial perpendicular veins, whereas folding and faulting play a minor role in the evolution of the folds. Non-axial-perpendicular extension fractures and faults were significantly developed only in narrow hinge zones. Strain history of the SJB and SB anticlines is relatively simple with a single history of layer-parallel contraction and shear verging toward the anticline crests.

from basin-wide tectonic signals.

Changes in sedimentary facies and paleosol types in the formations of the Chinle Group record a long-term climatic shift from tropical/humid in the Carnian to seasonal-arid conditions in the Norian. A similar climatic shift over this period is recorded in the Newark basins. This shift is thought to result from the northward drift of North America during the rifting of Pangaea, bringing the Four Corners region from a near equatorial position to the arid-zone latitudes.

11:45 AM Krumbein, Wolfgang E.

PHYSICAL AND CHEMICAL MODELS TO EXPLAIN BIOGENICITY OF SEDIMENTARY STRUCTURES

KRUMBEIN, Wolfgang E., BREHM, Ulrike and GERDES, Gisela, AG Geomikrobilogie, ICBM, Postfach 2503, D-26111 Oldenburg, Germany, WEK@africa.geomic.uni-oldenburg.de

Recently Grotzinger and Rothman (1996) suggested, that stromatolite-like structures may have been formed as surficial sediment structures by pure chemical/physical interactions between sediments and the water column without microbial participation in this interface activity. They conclude that morphology alone cannot decide about biogenicity and ask for clear evidence of microbial fossils. They further suggest the term 'abiogenic stromatolite', which seems wrongly worded, stromatolites being biogenic by definition. We present here data and analyses which document physical and chemical factors and models for biogenicity without the evidence of micro-organisms needed. Fairy ring structures are documented from potential stromatolites of saltems from the Bretagne and of Lanzarote. Specific diffusion related chemical reactions in microbial mats in the field and in a laboratory experimental saltern system are described. Although fairy rings have been always associated with fungal mycelia, the fairy rings recorded here are not related to this group of micro-organisms. A chemical reaction-diffusion model is suggested to explain the origin of these characteristic rings in microbial mats/stromatolites. Careful analysis and distinguishment between (i) potential stromatolites (recent microbial mats with a potential to diagenetically produce stromatolites), (ii) stromatolites (rocks with mineral and grain sequences and textures identified as a products of microbial mat activities) and (iii) stromatoloids (structures resembling stromatolites but without evidence of biogenicity) is necessary. Field observations, laboratory experiments and mathematical/physical models can help to establish biogenicity. Fossil remains of micro-organisms are not always needed to establish biogenicity of a stromatolitic structure which, by definition is a rock generated by physical, chemical and biological activities of microbiota. All three can be derived from observation and experimental approach followed by mathematical/physical modeling.

References: Grotzinger, J.P. & Rothman, D. H. (1996). An abiotic model for stromatolite morphogenesis. Nature, 383, 423-425.

SESSION 14, 8:00 AM

Monday, October 20, 1997

Structural Geology I: Fold and Thrust Belts

SPCC Ballroom H

8:00 AM Hardy, Stuart

PROGRESS TOWARDS ADVANCED RESTORATION AND FORWARD MODELING OF STRUCTURE IN CROSS-SECTION

HARDY, Stuart, and SUPPE, John, Department of Geosciences, Guyot Hall, Princeton University, Princeton, New Jersey, NJ 08544, stuart@geo.princeton.edu.

Existing restoration and forward modeling strategies, e.g. inclined simple shear or flexural slip, have been shown to work well on many natural structures. However, when structures become complex or more than one deformation mechanism is operative, simple kinematic approaches appear to have limited applicability. Here we propose a new methodology for restoration and forward modeling cross-sections using rigid element packing, based upon the observation that in the brittle upper crust much deformation is accommodated by the displacement of essentially undeformed blocks separated by bedding slip planes, faults, veins and stylolites.

Rigid element packing treats restoration and forward modeling as the problem of minimization of voids and overlaps between variously shaped rigid blocks subject to given displacement boundary conditions. The blocks are internally undeformed with any necessary displacements taken up on the boundaries between adjacent blocks. Through an iterative series of rotations and translations, voids and overlaps between blocks are minimized during packing. The power of the technique is that we assume no unique deformation mechanism to be operative. The displacement field is simply a result of the applied boundary conditions and the shape of the blocks (equilateral, elongate, etc.) and can approximate flexural slip, variably inclined simple shear or combinations thereof.

Simulations of a listric extensional sandbox experiments using equilateral elements predict complex hanging wall displacement fields in which apparent inclined shear angles vary from moderate dips in the upper part of the model to steep dips near the detachment surface, very similar to those reported from sandbox experiments. The technique has also been successfully applied to the restoration of outcrop and seismic examples of extensional and compressional structures and shows that the much of the observed deformation can be accounted for by rigid body translation and rotation. In addition to restoration of geometric elements (blocks) we have also restored outcrop photographic and seismic images contained within the blocks as an additional means of verifying and assessing a restoration.

8:15 AM Suppe, John

DEFORMATION OF THE UPPER CRUST BY RIGID-BLOCK ADJUSTMENT, FRAGMENTATION AND HEALING

SUPPE, John and HARDY, Stuart, Department of Geosciences, Guyot Hall, Princeton University, Princeton NJ 08544 USA

Upper crustal deformation is well known to involve diverse mechanisms including compaction, fracture, frictional sliding, pressure solution and the transition to plastic deformation. However the dominant process that accommodates large deformation in the upper crust is typically (but not universally) adjustment between adjacent rigid blocks that progressively form and heal on a hierarchy of scales. Thus, most rock in deformed structures in the upper crust has undergone no deformation other than rigid-body translation and rotation. The finite displacement field is dominated by block-boundary processes including faulting, gouge formation, vein and stylolite formation, and tensile fracture. The interiors of blocks are typically (but not universally) rigid.

The combination of outcrop studies by many workers and advanced restoration and forward-modeling capabilities based on rigid-element behavior (e.g. Hardy & Suppe, abstract) provides new insight into how the physical processes of rigid-block adjustment, fragmentation and healing add up to produce large-magnitude, map-scale deformations. For example, precise restoration of structures ranging in scale from 3D seismic to outcrop shows that at each resolution, almost all the deformation is by rigid-block adjustment and block-boundary processes. Field observations show that typical largest block sizes in 5-10 km-scale compressive structures are on the order of 10-100 meters with on the order of 100,000 large blocks in cross section. Smaller structures typically have smaller largest blocks. Forward structural modeling shows how these large blocks roll through hinge zones in map-scale fault-related folding.

8:30 AM Smart, Kevin J.

FRICTIONAL INTERPLAY OF TWO THRUST FLATS: INSIGHTS FROM FINITE ELEMENT ANALYSES

SMART, Kevin J., School of Geology & Geophysics, Univ. of Oklahoma, Norman, OK 73019, kjsmart@ou.edu; KRIEG, Raymond D., Dept. of Engineering Science & Mechanics, Univ. of Tennessee, Knoxville, TN 37996; DUNNE, William M., Dept. of Geological Sciences, Univ. of Tennessee, Knoxville, TN 37996.

Interesting issues in duplex-dominated thrust belts are the mechanical conditions that control the interplay of slip on the upper and lower thrust flats, and the relative timing of their movements. These issues assume particular importance when discussing whether ramps between flats move simultaneously or sequentially. In the first case, vertically stacked segments of both flats are active, whereas in the second case both flats are active, but not above each other. We use finite element models to evaluate the conditions that favor simultaneous versus sequential movement. Additionally, our investigation of the interaction of vertically stacked thrust flats may indicate where a ramp would initiate during sequential thrusting.

During previous modeling, we derived an equation relating frictional resistance and overburden to predict the relative friction values needed for simultaneous slip on two vertically stacked thrust flats. Here we test this equation with new models to address the conditions that: (1) favor initial activation of one flat over the other; and (2) control simultaneous versus sequential thrust displacement. Simple flat thrust sheet models with two vertically stacked sliding interfaces demonstrate a straightforward application of this equation. Constant material properties throughout the model focus attention on the effects of the thrust sheet thickness and frictional resistance on fault behavior. These models demonstrate that simultaneous slip requires the frictional resistance on the upper interface relative to the lower interface to be less than a critical value predicted by the equation. Tapered geometries with two vertically stacked flats assess how lateral variation in thrust sheet thickness effects the relative timing of movement on the two flats. While the lower flat activates first, the upper flat does subsequently begin slipping. The finite element models also demonstrate that simultaneous slip on two vertically stacked thrust flats is not only mechanically possible, but may actually be favored over sequential slip on the interfaces.

8:45 AM Strayer, Luther M.

SIMULTANEOUS FOLDING AND FAULTING AND FOLD-THRUST BELT EVOLUTION: A DISTINCT-ELEMENT MODEL

STRAYER, Luther M., and HUDLESTON, Peter J., Geology & Geophysics, University of Minnesota, Minneapolis, MN 55455

Using the distinct-element, finite-difference code PFC (Particle Flow Code) we have constructed 2D models of fold-thrust belt evolution. Faults develop as discrete, persistent 'damage' zones in the finite-difference mesh because rock material is represented by 3000 elastic balls (actually 2D disks) with 'micro'-properties: shear- and bulk-modulus and contact friction, defining the elastic behavior, and shear and normal bonds, joining the assembly into the continuous initial configuration. Bond strength and size distribution of the balls define the plastic behavior. Ball size is varied to avoid hexagonal close-packing; this means that the prototype is represented by rigid blocks of 'rock' ranging from 267m to 400m in diameter. The model is constructed by filling a rectangular region (100 km by 5 km) with loose balls, increasing the radii until they contact, allowing for compaction under gravity, and then bonding them into a continuous mass. Joint-sets, which are simply linear zones of weak bonds can be introduced. Individual 'beds' can be color-coded to track deformation. Boundary conditions are: the top is free, the base and sides are frictional. Shortening occurs by a right-directed velocity applied to the left wall.

Preliminary results of varying shear and normal bond strength show deformational styles ranging from fault-dominated, in which nearly all the bonds break, and the mass behaves as a sandbox model, to fold dominated, where faulting does not occur, but rather buckle-folds. Within this range lie models which display the folding and faulting common in fold-thrust belts. We have recognized: 1) both fault-bend and fault-propagation style folds; 2) rounded to chevron fold styles; 3) fault-horses/duplexes.

A number of important research directions are possible with models of this type. Because the model is composed of discrete particles it is a relatively simple matter to identify the upper surface and remove or 'erode' individual particles as a function of time or local surface slope (diffusion based), and also to redistribute or 'deposit' those particles downslope and onto the foreland. This would allow the relationship between erosion and tectonics to be investigated.

9:00 AM Thomas, William A.

VARIATIONS IN THRUST-BELT STYLE AS A FUNCTION OF DIFFERENCES IN THICKNESS OF THE BASAL WEAK LAYER

THOMAS, William A., Department of Geological Sciences, University of Kentucky, Lexington, Kentucky 40506-0053, geowat@pop.uky.edu

Structural style in thin-skinned thrust belts is controlled substantially by the stratigraphic succession and relative thicknesses of mechanical lithic units (stiff layers and weak layers). Classic long-wavelength listric frontal ramps from a stratigraphically persistent basal décollement depend on a relatively thick stiff layer underlain by a relatively thin weak layer (e.g., Cambrian-Ordovician carbonate stiff layer and underlying shale in the central Appalachians). In contrast, a stratigraphic succession lacking a thick stiff layer deforms in short-wavelength disharmonic folds and folded multiple-level thrust faults (e.g., lower Paleozoic mudstone-dominated succession in the Ouachitas). A relatively thick weak layer commonly forms large-scale triangle zones that frame broad synclines in an overlying stiff

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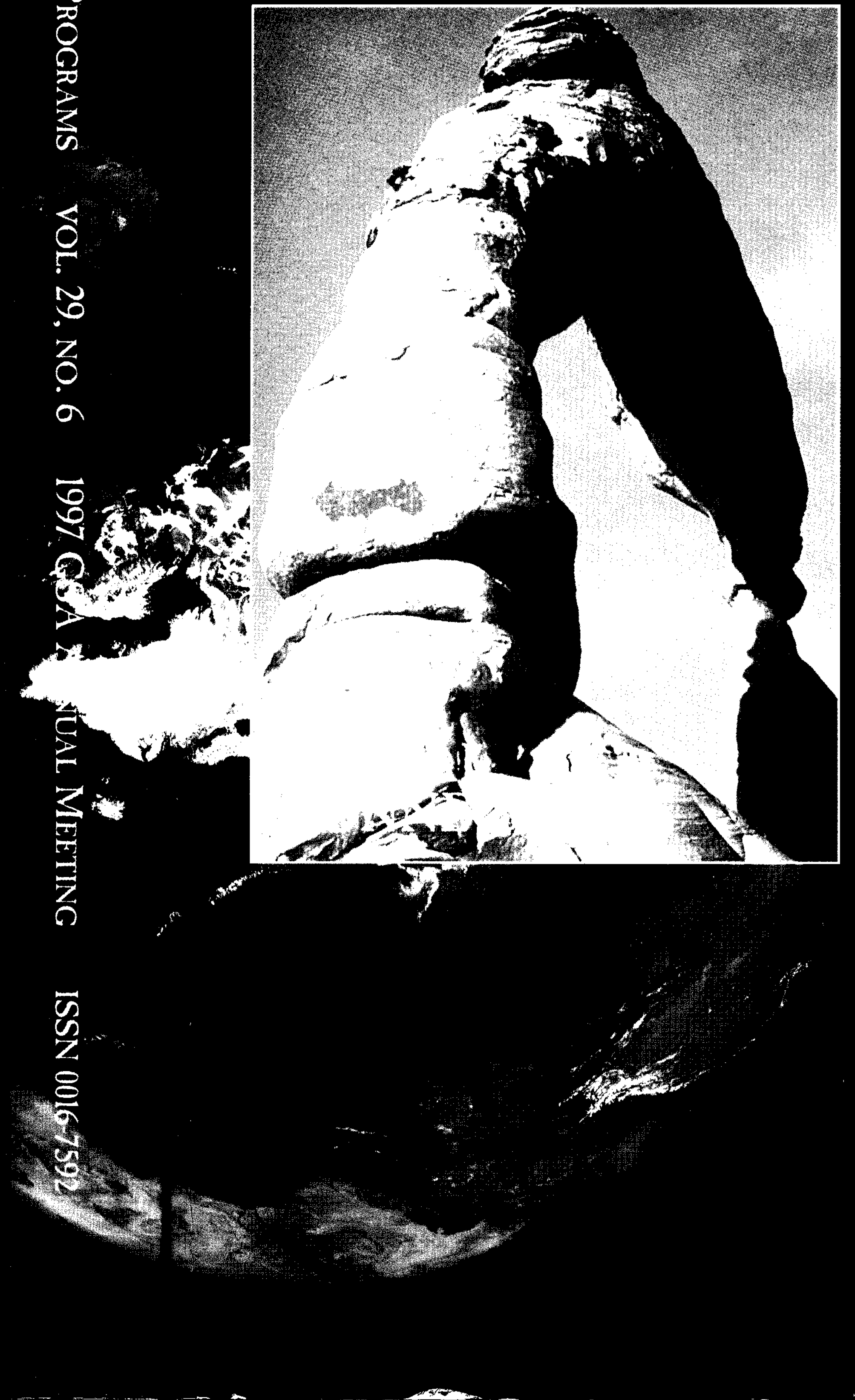

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